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A new experimental snow avalanche test site at Seehore peak in Aosta Valley (NW Italian Alps) – Part II: engineering aspects

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Keywords Avalanche dynamics; small and medium avalanches; experimental site; NW Italian Alps

Abstract *The estimate of the effects produced by the impact of a snow avalanche against an obstacle is of the utmost importance in designing safe mountain constructions. For this purpose, an ad-hoc instrumented obstacle was designed and built in order to measure impact forces of small and medium snow avalanches at Seehore peak (NW Italian Alps). The structural design had to consider several specific and unusual demands dictated by the difficult environment. In this article, the new test facility is described from the engineering point of view, discussing the most important aspects of the analyzed problems which were solved before and after the construction. The performance of the instrumented obstacle in the first two operating seasons, and some proposals for future upgrading are eventually illustrated.*

1 Introduction

The effects of the impact of snow avalanches on constructions located along their path should be estimated as accurately as possible when a sound risk analysis has to be performed and, even more, if adequate mitigation measures have to be designed. For this purpose, avalanches test sites at real scale have been designed in several countries in order to measure dynamical variables such as, for example, flow height, flow velocity and impact pressure. However, there are still some gaps in the understanding of the observed phenomena, especially regarding small/medium avalanches. In Europe, several test sites have been set up to study the dynamics of real avalanches (for a comprehensive review see, e.g., Issler et al. (1999) and Jóhannesson et al. (2006)): Col du Lautaret and Taconnaz in France, Núria in Spain, Ryggfonn in Norway, Vallée de la Sionne, Val Medel and Mettlenruns in Switzerland, Monte Pizzac in Italy, Großer Gröben and Schnannerbach in Austria, Flateyri in Iceland. These sites are generally equipped to measure avalanche velocity (mainly with radar techniques), shape and volume of the avalanche (image analysis), seismic and acoustic signals (mainly with geophones). The avalanche impact pressure on an obstacle, the most important parameter in designing safe structures against avalanches, is measured in some of the test sites by means of load transducers or indirect methods. Different types of obstacles exist at full-scale test sites, to simulate real buildings exposed to avalanches: beam-supported plate with adjustable height (Col du Lautaret), wedge-shaped mounds (Taconnaz), variable-angle wedge-shaped object (Monte Pizzac, Vallée de la Sionne), girder mast (Vallée de la Sionne, Ryggfonn), oval-shaped or circular tower (Ryggfonn, Vallée de la Sionne), impact wall (Vallée de la Sionne, Ryggfonn, Mettlenruns), roof of avalanche shed (Vallée de la Sionne), power line cables (Ryggfonn), stopping dam (Schnannerbach), dam with pole on top (Ryggfonn), tunnel-bridge with pressure transducers (Großer Gröben). Most of the sites were designed primarily to study large avalanches, which release spontaneously or, in some cases, through artificial triggering.

The present paper describes the new full-scale avalanche test site built in the Aosta Valley Region at Seehore peak (Figure 1), near the village of Gressoney-La-Trinité (NW Italy), designed to study the dynamics of small and medium avalanches, the avalanche release processes, and the interaction between avalanche flows and obstacles.

The Seehore test site is presented from the viewpoint of geology and snow science in a companion paper (Maggioni et al., 2012), where it is described in detail, starting from its location, morphology, snow and weather conditions and historical avalanche data. In this paper attention is focused on the design and construction of the instrumented obstacle placed along the path to measure impact forces. The conception of the test site took full advantage of the existing facilities, namely, the tracks that give access to the location and, most important, the close upper station of the Staffal-Gabiet cableway (2318 m asl), within the MonterosaSki resort. This building, permanently accessible during winter, was chosen as the optimal location for the control room of the measuring system. The instrumented obstacle is located mid-slope on the NW face of the

Seehore peak, about 550 m from the control room.

Once the site was chosen, the difficulties given by the natural environment, both in summer and in winter conditions, had to be considered in the design of the foundation and of the structures of the instrumented obstacle. One of the goals of this research was to build a structure reasonably safe under all the forecasted working conditions, able to carry the sensors and to record, automatically, the data measured during natural and artificially triggered avalanches running down the slope.

The design of the experimental site started from the analysis of previous experiences. In particular, the French site of Col du Lautaret (Thibert et al. (2008), Thibert and Baroudi (2010)), the Italian site of Monte Pizzac (Sommavilla et al. (1997), Sommavilla and Sovilla (1998)) and the Swiss site of Vallée de la Sionne represented a source of inspiration and information (Ammann (1999), Dufour et al. (2000)). The Seehore test site, in addition to some features common to existing sites, such as easy accessibility, capability of artificial releases, and possibility to record natural events, possesses some unique characteristics. The impact forces are measured directly by an array of load transducers placed at different heights on a vertical structure, not requiring the processing of cumbersome deformation measurements, as in other test sites. Moreover, the Seehore obstacle was conceived to be easily maintained or refurbished to upgrade the measuring capability.

Furthermore, the steel structure is composed of two separated, yet connected parts, allowing the installation of obstacles with different shapes. On the basis of the principles of capacity design in structural engineering, the two parts have been connected in order to prevent any damage to the foundation of the obstacle in case of exceptionally large impact forces. The following sections describe the engineering aspects of the design and construction of the Seehore test site, which can be grouped into three main categories: safety of the site, structural conception, data acquisition and control. An account of the results recorded during the first two winter seasons concludes the paper.

2 Safety of the site

2.1 General

The site chosen for installing the instrumented obstacle is a fairly steep natural slope (Maggioni et al., 2012). A number of human activities had to be carried out on the slope, both during the construction of the obstacle and during service operations. For this reason, a main issue was to check the slope stability in order to ensure the safety of working operations. In order to characterize the site, geological and geophysical surveys were carried out and slope stability was analyzed into details.

2.2 Geological features and slope stability

The chosen experimental site at the Seehore peak (Figure 1) has an aspect of about 350°, and the width of the couloir is in the range between 40 to 80 m.

Close to the location of the instrumented obstacle the following types of coverage were observed (see Figure 2):

- Gravitational deposits of a scree and an alluvial fan: it is mostly very coarse material, consisting of angular blocks typically of decimetre size, but also larger, practically without fine matrix, at least on the surface;
- Accumulation of rockfall blocks: these are very coarse deposits, sometimes with metric-sized blocks.

In order to investigate the characteristics of the rock mass and to quantitatively assess the thickness of the debris layer covering the slope, a campaign of geophysical surveys was carried out, through the acquisition of electrical and seismic tomography.

The results of the measurements, interpreted with the tomographic technique have revealed the presence of bedrock, highly fractured and not saturated, only at the sides of the couloir. Nowhere else the presence of a compact rock mass was detected. The stratigraphy of the rock mass in the obstacle area down to a depth of 15-20 m can be defined as constituted by a layer of detritus deposits without clay fraction having a thickness of about 10 m, lying upon a highly fractured and weathered bedrock with poor quality.

Although the slope near the obstacle is naturally stable, the debris layer could release shallow landslides when avalanche impact forces would act on the ground through the obstacle foundation. Slope stability has been analyzed through the limit equilibrium method: the results show that stability is guaranteed on the slope above the obstacle and below its foundation for the worst scenario, with a safety factor (the ratio between the structural capacity and the applied load) larger than 1.2.

Four families of discontinuities have been identified. Some of them intersect, allowing the formation of potentially unstable rock wedges characterized by steep intersection lines. These are very critical for the stability. Wedges, sliding or toppling from the outcrops in the area above the obstacle, continue their motion giving rise to rockfall, which affects the whole area of interest.

The stability of the site with respect to rockfalls has been analyzed by using a probabilistic approach and the lumped mass method (Rocfall code, see ROCSCIENCE Inc., Toronto (Canada) (2004)). The two most likely paths of the snow avalanche have been chosen for the slope profiles. Characteristic volumes for the rock block were chosen between 0.06 and 0.56 m^3 (masses of 150 kg and 1500 kg, respectively) and an initial velocity equal to 0.6 ± 0.1 m/s was assumed. A number of back analyses allowed to determine the coefficients of restitution.

The results provided a maximum value of kinetic energy of about 75 kJ (maximum velocity of about 10 m/s), maximum bounce height of about 2 m and a very low probability that the blocks impact the obstacle. However, all

the simulations showed that most of the blocks stop just above the obstacle, thus rockfalls had to be taken into account in order to ensure adequate safety of the operators, during construction and maintenance of the obstacle.

3 Design of the obstacle

The obstacle and the measurement systems rest on a concrete slab 3 m long by 3 m wide and 0.6 m thick, placed approximately in the position shown in Figure 2. They were designed to resist the impact of avalanches running along the path and to measure velocity and impact forces. The foundation was embedded so that it emerges only 0.6 m from the natural slope. Gabions filled with material readily available on site were used to support the excavation; this choice helped to minimize the environmental impact, also reducing the amount of concrete to be cast in place (Figure 3).

The following main parts were assembled (Figure 4):

1. a vertical obstacle made of galvanized steel profiles (4.0 m high, protruding 2.8 m from the natural slope profile), consisting of a lower section bolted to the concrete foundation, serving as a support for the upper part which carries the sensors, directly exposed to the avalanche impact;

2. a sealed electric cabinet that hosts the acquisition and control systems, terminal of the power supply line and of the optical fiber of the data transmission line, connected to the upper station of the Staffal-Gabiet cableway;

3. a galvanized steel shed that protects the cabinet from the direct impact of the avalanches and provides also a walking surface to reach the upper part of the obstacle for inspection and maintenance works.

The main function of the obstacle is the measurement of velocity and impact forces generated by snow avalanches. The impact surface mounted on the structure is large enough to reproduce a small portion of a real building, and at the same time, to allow the safe operation of the system under the expected loads. The surface is arranged in a vertical plane perpendicular to the main flow direction. At the top of the upper steel frame, velocity sensors can be placed, exploiting image analysis techniques.

The impact surface is made of an array of 5 aluminum grooved plates placed at different heights, each one supported by two load transducers, which are connected to the structure. The load transducers are, in turn, mounted on slides that can be easily moved along vertical guides: this design permits their positioning at the desired height above the ground level. The total area of the impact plates is 1 m^2 (Figure 4).

Lacking specific information on the values of the expected forces, a design pressure of 50 kPa was assumed. This value is consistent with numerical simulations carried with the software AVAL-1D, developed by the Swiss Federal Institute for Snow and Avalanche Research (SLF) in Davos (Christen et al., 2001),

assuming as model input the typical snow depth values used as a threshold for activating the artificial release procedures. It is worth noting that the threshold to operate an artificial release is around 30 cm of fresh snow (Maggioni et al., 2012). At the French site of Col du Lautaret, similar in some respects to the Seehore site, the forces measured on an obstacle with an impact area of $1\,m^2$ are about 35 kN (Thibert et al., 2008).

In addition to the action of avalanches, a number of loading conditions have been taken into account in designing the structures and the foundation of the platform, namely, the slow action of the snowpack due to gliding, the vertical pressure of snow, wind pressure, earth pressure, seismic effects. The structural integrity was verified according to the Italian building codes (Consiglio Superiore dei Lavori Pubblici, 2012). The gliding actions were evaluated according to the Swiss rules (Margreth, 2007).

The safety factor of the foundation is calculated under the assumption that the action of the avalanche does not exceed the nominal value of the design force. As the evaluation of the impact force is the main goal of the experimental site, it cannot be excluded that its actual value could be higher than the limit load used for the design. Moreover, due to the hard constraints dictated by the difficulties of construction on the site, design had to chose a shallow foundation with relatively small size. This was an obliged choice, in order to limit the excavation works on the steep slope, and excluding other solutions as micropiles or anchors, due to economical and environmental requirements.

To ensure adequate safety margins to the platform in all the operating conditions, the decision was made to limit the load on the foundation, by sacrificing the structural integrity of the instrumented obstacle when an impact force would reach the prescribed limit value. To this purpose, the link between the lower and upper parts of the obstacle was designed as a weak point with a predefined limit load (Figure 5). The design followed the rules of capacity design, i.e., the increasing loads activate a prescribed sequence of failure mechanisms. According to these principles, the design of the structure is calibrated in such a way that the foundation would always be safe, even under extreme events.

In order to validate the design assumptions, a number of tests have been carried out at the laboratory of structural mechanics of the Department of Structural, Geotechnical and Building Engineering of the Politecnico di Torino. The complete structure had been assembled within a specially built testing frame in order to place the obstacle in a horizontal position (Figure 6).

In particular, experimental modal analysis has been performed in order to assess the dynamic properties of the obstacle and to validate the results obtained from numerical analyses (Figure 7), performed with the finite element code ADINA (ADINA R&D, Inc. (2012)).

In addition, static tests leading to failure of the load limiter device have been conducted, simulating different real loading conditions. Some results are presented in Figure 8, where the total load applied by the testing machine on the obstacle is plotted against the relative displacement of the load limiter plates.Such tests have been carried out for different distances of the load limiter plates, i.e., for different length of the steel bars linking the lower and the upper

part of the obstacle.

4 The instrumented obstacle

4.1 General

The obstacle is equipped with a number of sensors that measure different parameters needed to improve the comprehension of the interaction between avalanches and constructions. Among the different mechanical variables that characterize this interaction, the focus has been put on the impact pressure and on the acceleration caused to the structure itself by the impact. In addition, the environmental variables, i.e., air temperature and atmospheric pressure are measured. Velocity sensors at the top of the upper steel frame will be mounted in the next future.

One of the constraints for choosing the measurement devices system was the use of commercially available components only. This design attitude was dictated by the desire, on one hand, to limit the investment costs and, on the other hand, to add flexibility in the maintenance and replacing procedures of damaged parts.

The system conceived to fulfill the design tasks were divided logically into two main parts, namely, 1) the measuring and data logging part, located on the platform, near or onto the obstacle; 2) the data storage and control in a remote room, safe and easily accessible. The two parts are physically connected by a power line and an optical fiber for data transmission, both lying in a buried PVC duct, which ensures a permanent and reliable link. The control room is also connected, via cellular network, to the Internet, providing the possibility of remote operations. A scheme with the connections between the parts of the system is shown in Figure 9.

The ultimate goal of the designed system is to achieve fully automated operation, able to provide recording of both natural and artificially triggered avalanche events, without any human intervention. The final setup has been reached through four operational levels:

1. manual recording procedure activated by an on-site operator;
2. manual recording procedure activated by a remote operator (via Internet);
3. automated recording procedure self-activated by the avalanche impact;
4. automated recording procedure self-activated by the avalanche impact and automatic reporting.

The detailed description of the devices composing the system is given in the following sections.

4.2 Data logging and control

The core of this subsystem is a real-time controller (National Instruments CompactRIO 9014), with 2 GB of non-volatile memory, Ethernet port, built-in FTP and web servers. It is mounted on a 8-slot chassis for the interface modules of the measuring instruments, which are:

- 3 modules for extensimetric bridges (NI-9237), each one with 4 channels, used to power the load transducers, to condition the signals and acquire the measurements. The maximum sampling frequency for every channel is 50 kHz, with 24 bit resolution.
- 1 module for thermocouples (NI-9211) with sampling rate of 14 Hz and 24 bit resolution.
- 1 module with 4 channels for integrated electronic piezoelectric sensors (NI-9234), used for measuring acceleration, with sampling frequency up to 51.2 kHz per channel and 24 bit resolution.
- 1 module with 32 analog input channels (NI-9205), used for the measurement of the atmospheric pressure, with maximum sampling frequency of 250 kHz (total), and 16 bit resolution.
- 1 module for solid state SD memory expansion (NI-9802) to 4 GB.

4.3 Transducers

In principle, any type of devices that measure physical quantities of the impacting avalanches can be installed on the obstacle. The present setup of the measuring system enables the measurement of the impact forces and of the acceleration of the resisting structure. A scheme of the installed sensors is shown in Figure 10.

The impact forces are measured with 10 transducers U10M, made by HBM-Messtechnik, with nominal load of 5, 12.5 and 25 kN, accuracy of 0.2 %, with degree of protection IP67 and operating temperature range between −30 to +85 °C.

The initial design specified the usage of 5 kN load transducers for all the impact plates, but after some failures due to overloading occurred during the first operating season, the nominal range of the transducers in the lower position has been increased. Moreover, in the original design the plates were rigidly connected to the load transducers. For this reason, the bending moments that may develop during an impact could contribute to overload the transducers and exceed their capacity. To eliminate this potentially dangerous effect, an hinged joint has been introduced together with a sliding connection of the plates, so that undesired bending moments transmitted to the measuring instruments are avoided.

To detect the onset of motion of the structure under impact, and to monitor its behavior during the transit of the avalanche, 4 accelerometers have been

fixed to the upper part of the obstacle, in different positions and orientations. They are uniaxial preamplified piezoelectric accelerometers Endevco 751-100, with integrated electronics. These instruments have a wide bandwidth (from 1 Hz to 15 kHz), nominal acceleration sensitivity of 100 mV/g and temperature operational range between −55 and +125 °C.

The pressure transducer is a PMP 4010, made by GE Sensing, with measuring range from 800 to 1200 mbar and accuracy 0.04 %. The sensor is fixed to the upper part of the structure, near its maximum elevation, in such a way that it cannot be directly hit by the avalanche.

The temperature transducers are T-type thermocouples (copper-constantan), with sensitivity of 48.2 µV/°C, whose hot joint is insulated within a stainless steel capsule. Four sensors are located on the upper part of the obstacle, at elevations of 0.1, 1.0, 1.9, and 2.8 m above the intermediate flanges.

4.4 Operating modes

The measuring system is controlled and monitored by means of a software developed within the programming environment LabView, produced and licensed by National Instruments. Two operating modes are possible, depending on the experimental conditions:

1. *manual mode*, when the sensors are activated by the operator command, typically several minutes before an experiment, and recording of data is started when the first motion of the avalanche is detected and communicated by another operator, which is in sight of the obstacle. Another communication informs the operator about the end of the event to stop the recording.

2. *automatic mode*, when the sensors are permanently kept active, and the recording procedure is triggered by a given threshold attained by one of the signals, e.g., the acceleration of a point of the structure (listening state). Data recording starts when the trigger is activated and proceeds for a given time, typically 30 s, then the system resets again to the listening state.

In both cases, measured data are temporarily stored in the data logger in files containing each one 1 s of recording, with sampling frequency of 2 kHz, with the exception of the temperature measurements.

The recorded data are then transferred via FTP to the PC located in the control room via the Ethernet LAN. The PC can be operated locally, when the experiments are attended in manual mode, or remotely, acting through the GPRS router that gives connection to Internet.

An example of the recorded data is shown in Figures 11 and 12, where the signals obtained from two sensors (an accelerometer and a load transducer), converted to engineering variables, are plotted for a time interval of 5 s beginning about 0.2 s before the impact of an avalanche.

5 First seasons of operational activity (winter 2010/11 and 2011/12)

The instrumented obstacle at the Seehore test site is active since November 2010. During that winter, the system was active in the operational levels 1 and 2 (see section 4.1), i.e., was functioning in manual mode (section 4.4). The site manager, generally 3 days before the planned triggering of an avalanche, alerts a team of operators which reach the site with the task of collecting different kinds of data and activating the acquisition system few seconds before the release, in order to record and save impact forces data (operational level 1). This procedure, albeit necessary to evaluate directly the functionality of the system at the beginning of its activity, is expensive and time consuming. A first improvement was obtained by implementing the remote operativity (operational level 2), where the switch on of the system is made from any PC connected to Internet, on request of an on-site operator.

During the winter season 2010-2011, several avalanches where artificially triggered at the site (Maggioni et al., 2012), and for some of them it was possible to acquire significant impact data. Despite the limitations of the operating mode, also two unplanned events were observed: the first one was a natural avalanche that hit the obstacle at the very beginning of the winter, causing a minor damage to the bars of the load limiter device, which was quickly repaired; the second one occurred towards the end of the winter and was a catastrophic event, which led to the loss of functionality of the whole system. In this case the avalanche impact caused the complete separation of the upper part of the obstacle, dragging it about 20 m downslope and ripping out all the electrical wires.

Other minor improvements described in section 4.3 have been introduced on the basis of the experimental results of the first seasons.

After large reparation works and improvements, during the winter 2011-2012 the system was working in automatic mode (see section 4.4), at the operational level 3 (section 4.1). In automatic mode, during winter 2011/12, the system was activated about 200 times, but only in two cases important avalanches occurred.

6 Summary and outlook

The first seasons of operativity of the site can be judged in two different ways. First, the planned operational modes were defined and tested. In parallel, some events whose magnitude was unknown in the design phase were observed and proper solution were found. In particular, the two unplanned events confirmed the soundness of the structural design. The load limiter device worked properly, preserving the lower part of the obstacle and the platform underneath from damage. Besides, the lesson learned from these strong events suggested some improvements to the design: for example, the wiring of the sensors system has been modified in order to allow a fail-safe sectioning in case of large movements of the upper part of the obstacle.

The analysis of the first measurements highlighted that the initial assumption of uniform pressure on the obstacle, and the consequent choice of the load capacity of the force transducers, was not conservative and led to damage of some of them due to unexpectedly large load concentrations on single instruments. Thus, load transducers sensors were modified with stronger capabilities. This inhomogeneity should be taken into account when addressing the avalanche impact on real buildings.

The large number of automatic recordings during winter 2011/12 helped in fixing the correct value of threshold acceleration for the automatic activation system, and in setting up the algorithm for identifying real avalanches and generating automatic reports. In the current 2012/2013 winter season, the design specifications are fulfilled and the site is fully functional.

The modular conception of the system is open to the implementation of measurement of other quantities, for instance: the velocity of the flow around the obstacle, which now is indirectly measured by videogrammetry, and the density of avalanche flow, which will be done in the next future.

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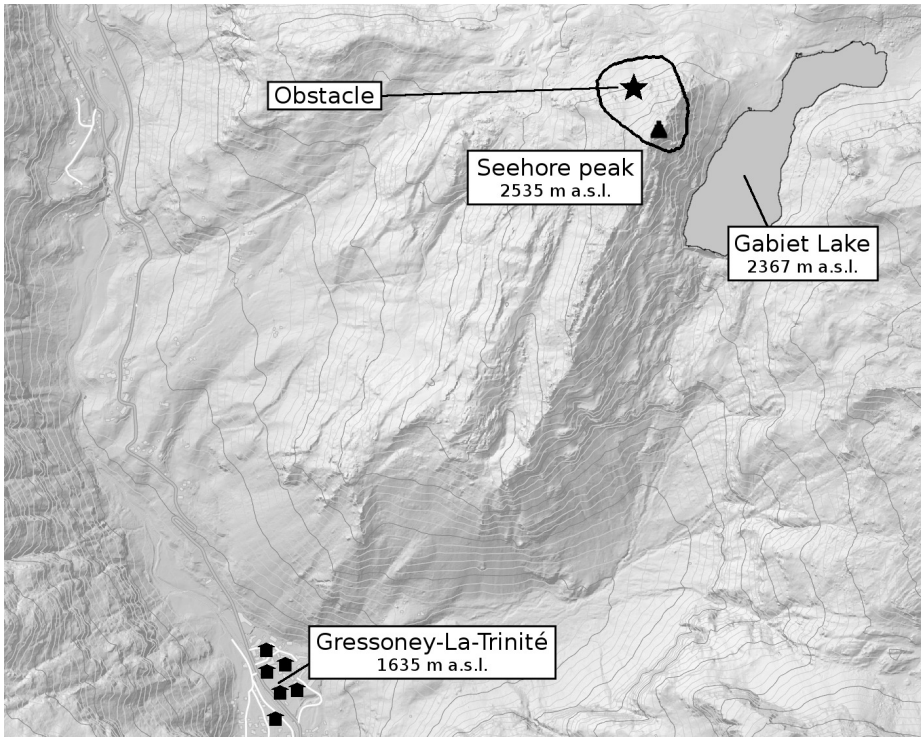

Figure 1: Map of the surroundings of the Seehore peak.

Figure 2: Frontal view of the test site in summer. The arrow marks the obstacle position.

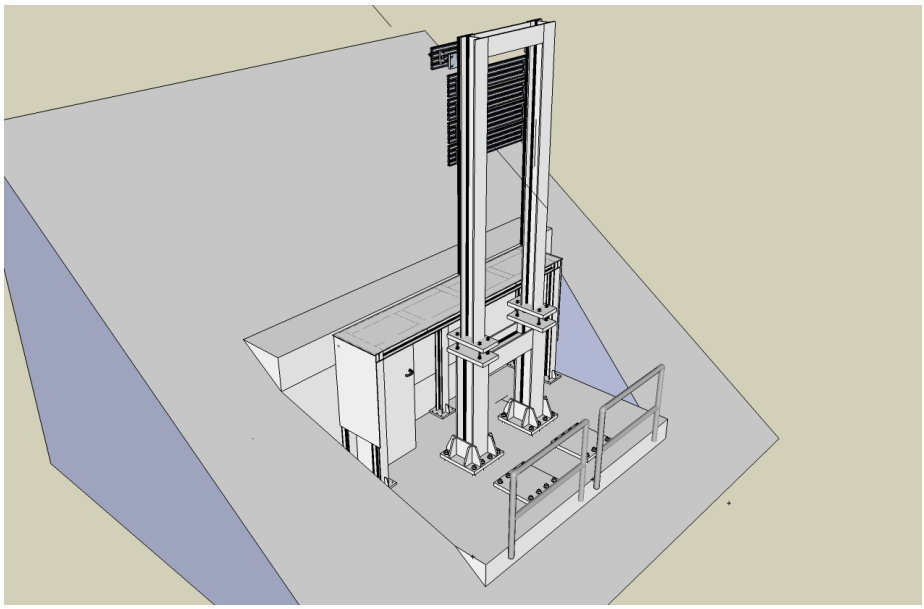

Figure 3: Sketch of the platform with the obstacle and the shed behind.

Figure 4: View of the obstacle after an avalanche event. Only the upper part of the steel structure emerges from the snowpack.

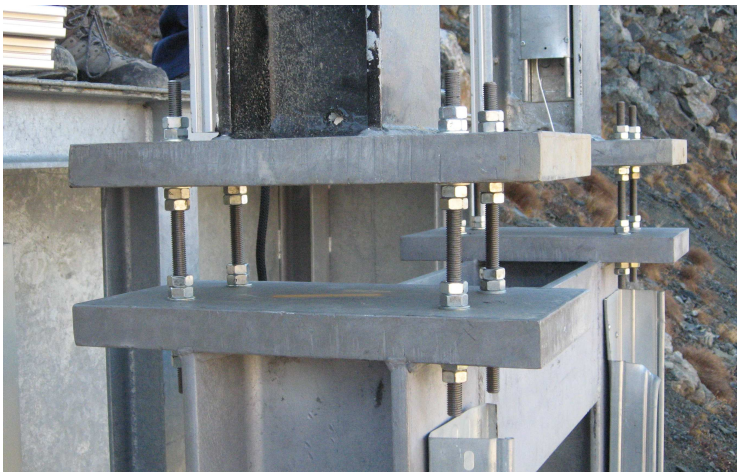

Figure 5: Detail of the load limiter device linking the two parts of the obstacle.

Figure 6: The obstacle mounted in horizontal position as tested in the laboratory.

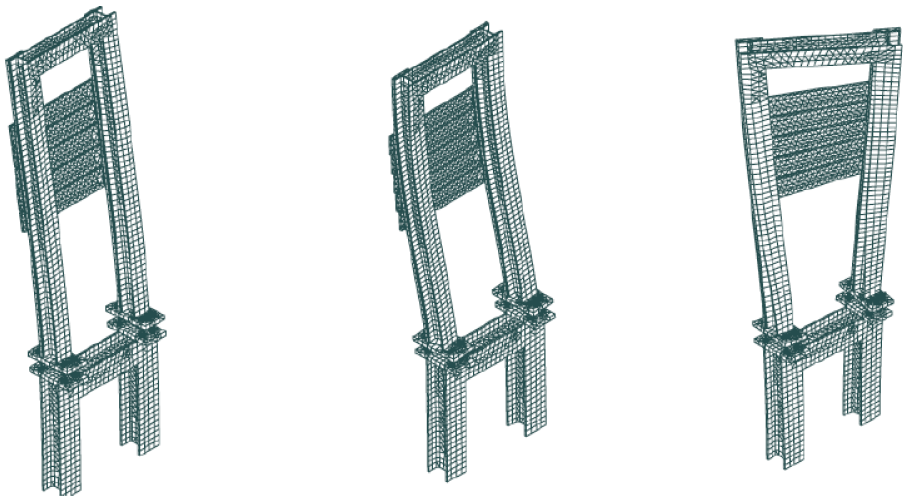

Figure 7: First three modes of vibrations, corresponding to the lowest frequencies, obtained through a numerical simulation.

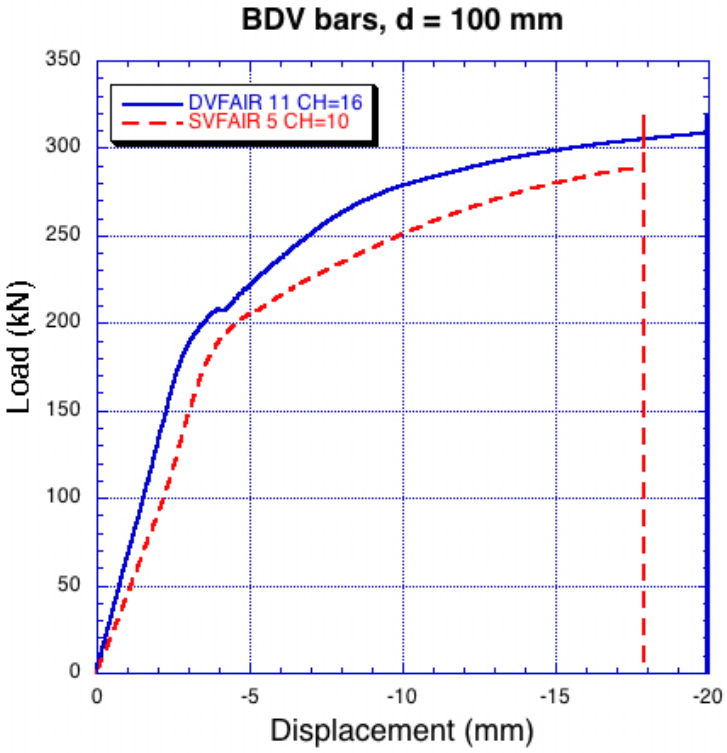

Figure 8: Total load vs. relative displacement for left (dashed) and right (solid) load limiter device (distance of load limiter plates equal to 100 mm).

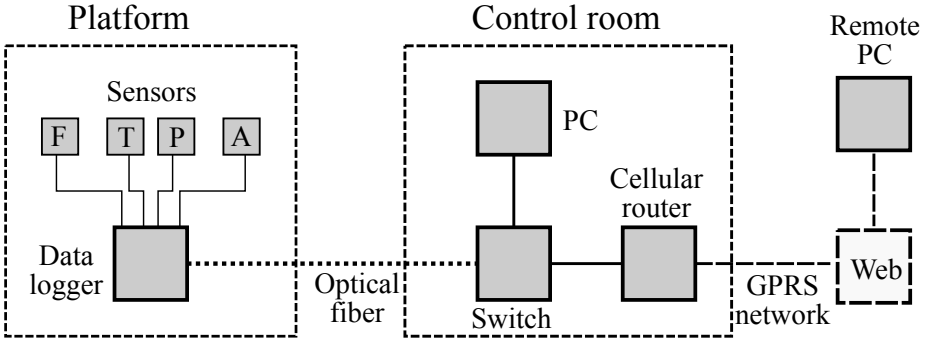

Figure 9: Block diagram of the communication network of the system. F, T, P, A denote the physical quantities measured by the groups of sensors: force, temperature, atmospheric pressure, acceleration, respectively.

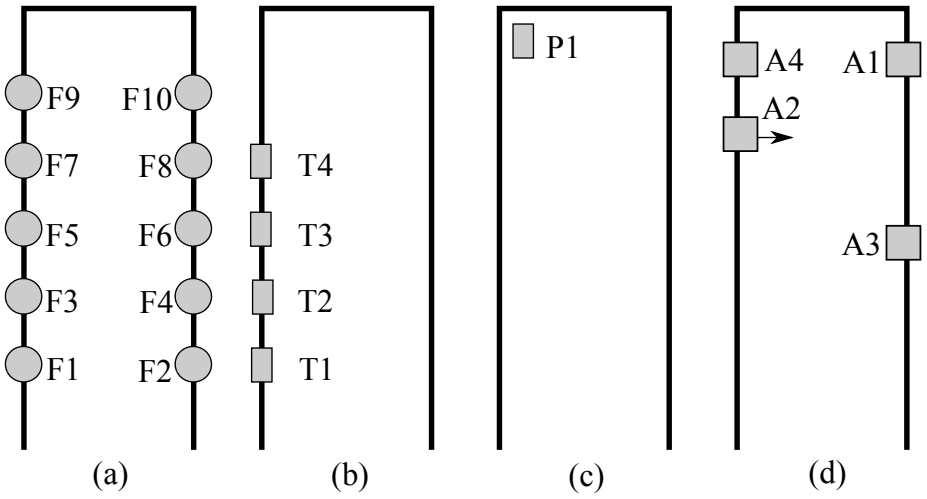

Figure 10: Schematic of the position of the sensors on the upper part of the obstacle, as seen looking downslope. Transducers of force (a), temperature (b), atmospheric pressure (c), acceleration (d).

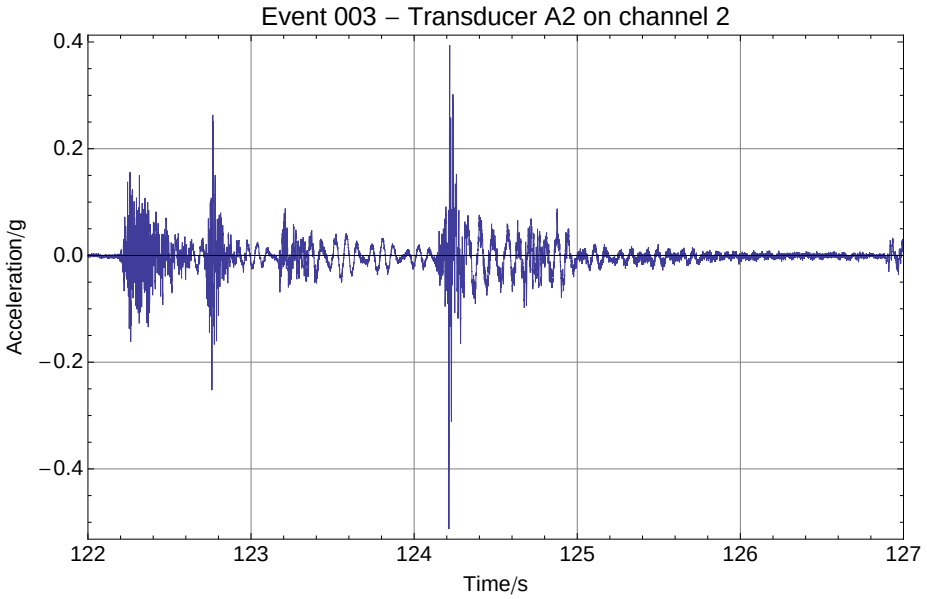

Figure 11: Example of measurements of acceleration plotted vs. elapsed time for an artificially triggered avalanche.

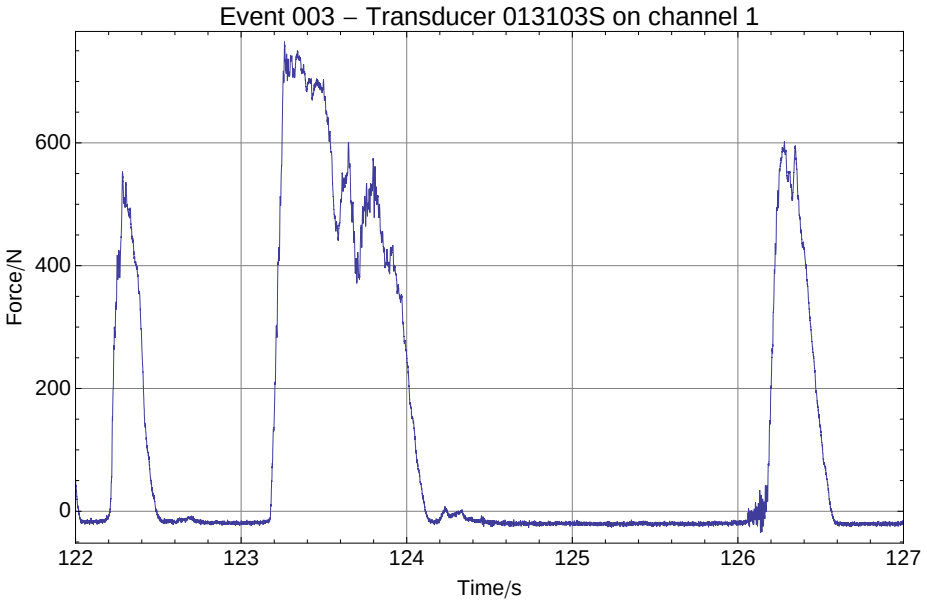

Figure 12: Example of measured force plotted vs. elapsed time for an artificially triggered avalanche.