DELIVERABLE D10

Documentation of instrumentation and installation details

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Editor's Foreword

This report describes the instrumentation work carried out during the SATSIE Project (Avalanche Studies and Model Validation in Europe, Contract n. CT2002-00059) in a group of selected experimental facilities, ranging from full-scale avalanche sites (Ryggfonna in Norway, Taconnaz in France and Flateyri in Iceland) to small-scale facilities, including the snow chute located in high-mountain terrain (Col du Lac Blanc, France) and laboratory granular chutes (Pavia, Italy).

A substantial technical and financial effort was made in order to improve the instrumentation of the mentioned facilities and to be able to perform comprehensive experimental investigations on the dynamics of avalanches, with special attention paid to poorly known aspects such as flow regimes, erosion processes and interaction of the flow with obstacles of various sizes and shapes. The facilities have been selected so as to maximise the variety of the experiments that can be performed, especially varying the size from laboratory-scale to full-scale, whilst insuring that the experiments are repeatable and as easy as possible to perform. The instrumentation of the considered facilities has been consistently improved in order to obtain more complete and accurate information on the important physical processes of avalanche dynamics. The first experimental campaigns carried out during the project encouraged us to go on with our work, with the belief that improving the knowledge of the phenomenon is an essential step towards improved simulation models, which are crucial tools for reducing avalanche risk and increasing the safety and quality of life of people living in avalanche-prone terrain in Europe and elsewhere.

Important outcomes of the SATSIE project that complement the present report are Deliverable D6: "Summary publication on sensor development and data analysis techniques", Deliverable D11: "Summary publication on small and full-scale experiments" and Deliverable D12: "Summary publication on avalanche/dam interaction measurements".

I am grateful to all the SATSIE partners cited in the frontispiece for their essential contribution to this report and to Dieter Issler for his precious revision work. The spelling, grammar and style were checked by Jim McElwaine to whom I am indebted for this important but tedious chore.

Pavia, October 2005

Massimiliano Barbolini
1. Instrumentation of the Ryggfonn test site

1.1 General description of the facility

The Ryggfonn full-scale avalanche test site (Lied et al., 2001), located at 61.969°N 7.275°E, has been in operation since 1980. During a period of 22 years, an average of 2–3 avalanches per year has been released in the path. The Ryggfonn avalanche (see Figure 1.1) has a vertical drop of about 900 m and a horizontal length of about 2100 m. The avalanches range in magnitude from 10,000 m$^3$ to 500,000 m$^3$, with maximum velocities up to 60 m/s. In the lowest part of the avalanche path, there is a 16 m high and 75 m wide retaining dam, see Figure 1.2.

![Figure 1.1 – An avalanche at Ryggfonn](image-url)
In the ground, from the top of the dam to 60 m up-slope from the dam, there are 5 vertical geophones, measuring ground vibrations (see Figure 1.3). All geophones are low-cost SM-6 or HS-1 sensors from Geo Space LP. 230 m up-slope from the dam is a 4.5 m high concrete structure fitted with three single-axis load plates, each with an area of 0.72 m² and a weight of 150 kg (see Figure 1.4). The design load for these plates is 600 kN. 320 m up-slope from the dam, a 6 m high tubular steel tower is fitted with a horizontal geophone and two single-axis load plates of the same type as on the concrete structure. The tower consists of three sections, each having a diameter of 1335 mm and plate thickness 15 mm, see Figure 1.5. Both load plate types are based on load pins with strain gages as the sensing elements.

The instruments in the avalanche path are connected by cables to an instrument shelter containing data recording equipment, a computer and the Doppler radar cabinet. The distance from the dam to the instrument shelter is about 450 meters. Signals from all sensors are measured by a data logger (Hottinger Baldwin MGCPlus) and stored internally after trigger events. Transfer of data from the logger to the computer is done manually. All sensors are sampled at a rate of 150 Hz and low pass filtered with a filter cut-off frequency of 40 Hz. The computer, which controls both the radar and the data logger, can be controlled from NGI’s office in Oslo, and data may be transferred there after avalanche events.
Figure 1.3 – Cross section of the Ryggefonna run-out area. Red arrows mark the positions of NGI’s geophones. Blue arrows mark geophones from the University of Barcelona

Figure 1.4 – The concrete structure with 3 load plates
1.2 Instrumentation work carried out during the project

1.2.1 Load plates

In September 2003 two tri-axial load plates were installed in the dam front, in order to investigate avalanche forces against big obstacles in the run-out area (Figure 1.6). The load plates, each with an area of 1 m², measure forces along three axes, the normal forces perpendicular to the dam, and two orthogonal shear forces in the plane of the dam front. The plates are designed for shear forces up to 200 kN and normal forces of 400 kN.
Figure 1.6 – Installation of the load plates in the dam front
1.2.2 Seismic sensors

Two tri-axial geophones were installed by the University of Barcelona team at the Ryggfonna site in September 2003, with active participation and help from NGI. The goal is to obtain seismic signals from naturally and artificially triggered avalanches occurring in the main avalanche path and on surrounding slopes. The results from the analysis of the information contained in the seismic signals themselves, and from their comparison with data from other instruments located in the path, can be used to infer details of the snow avalanches and also possible to detect avalanches. The instruments and installation system were designed specifically for the site (Figure 1.7). The seismic equipment is commercially available, but adapted to our needs, including waterproofing. It consists of:

a) two seismic sensors of LE-3D/5s type manufactured by Lennartz electronic GmbH (Fig 1.8);

b) a Reftek DAS 130-01 data logger (Fig 1.9).

Figure 1.7 – Seismic sensor installation in the track

Figure 1.8 – LE-3D/5s Lennartz Geophone
The seismic sensors were installed at the following locations (Figure 1.10):
- Sensor B is placed in the track at the bottom of an 80 cm diameter and 1 meter deep hole located 100 m above the dam along the avalanche path. Within 2 m from this place two other holes are hosting the FMCW radars (see § 1.2.3).
- Sensor A is installed 500 m along the valley from sensor B and 40 m away from the instrument hut. It is located at the bottom of a 40 cm diameter and 60 cm deep hole.

The data logger is placed in the NGI instrument shelter (Figure 1.10), and connected to a GPS system, which provides a very accurate time reference. The logger is configured to continuously record the seismic data from the two sensors in a ring-buffer system. Data are stored in duplicate because two data streams are recorded simultaneously: one in a triggered mode and the second data stream in a continuous mode. The triggered mode uses the trigger system of NGI's geophones. The purpose of this set-up is to synchronise the time stamp of the seismic signals with that of the data from the other
sensors installed in the path. Data are sampled at 200 Hz. The pre-trigger interval is 9 s and the total length of the record is 150 s including pre-trigger. In the continuous mode data are stored on an external USB hard-drive of 60 GB, connected to the existing NGI PC located in the instrument shelter. This capacity allows storage of 300 days of seismic data from the two seismic sensors. The data logger stores all the recorded data in its internal hard-disk and on the external USB hard-drive connected to the PC, if electric power is available in the hut. From the continuous data stream an event (avalanche, rock fall or earthquake) is extracted as a data file of five minutes duration with a sampling rate of 200 Hz.

A UPS (uninterruptible power supply) is installed to avoid file corruption and system hang-up during the frequent power failures in the instrument hut. There is direct communication with the data logger, for controlling the system and downloading the data, from Barcelona via a telephone modem. There is an Ethernet connection from NGI’s PC to the NGI office in Oslo.

1.2.3 FMCW snow profiling radar

Figure 1.11 shows a schematic overview of the FMCW (Frequency Modulated Continuous Wave) snow profiling radar set-up. There are four radars placed in two pairs. One pair is placed at the foot of the dam and the other is 100 meter up-slope. The purpose of this configuration is to try to measure cross-correlations at different depths between the radar signals of one pair and thereby to estimate down-slope velocity profiles.

![Figure 1.11 – Schematic overview of the FMCW snow profiling radar set-up](image)

The main features of the radars are summarised as follows:
- Frequency band: 2.6–4.6 GHz
- Detection range for normal snow: > 15 m
- Range resolution for normal snow: < 0.15 m
- Range accuracy: resolve the propagation time to better than 0.5 ns
- Measurement speed: > 100 Hz
- Separate transmit and receive wide-band 8-element array antennas
- Small antenna opening angle normal to avalanche direction, large in transverse direction
- Both the radars and the controlling PC are completely reprogrammable from NGI
- Size of electronics unit: < 0.5 \times 0.3 \times 0.2 m
- Mechanical: Waterproof, survives heavy loads and direct impacts
- Operating temperature: −40 to +50 C
- Operation principle: Stand-alone programmed automatic operation, externally triggered by geophone or pressure plate
- Data collection: Local storage of data during measurement, transferred to PC after measurement

All four radars were installed and connected to the data acquisition system in late September 2004 (see Figure 1.12).

![Figure 1.12 – FMCW radars before and after installation in September 2004](image)

### 1.2.4 Pulsed Doppler radar

Two sites were prepared for the deployment of the pulsed Doppler radar systems (Figure 1.13). These systems emits short radar pulses and sample the echo in distinct time intervals, corresponding to distance intervals (range gates). Frequency analysis of the echo signal calculates the energy in each spectral band. This can then be used to deduce the velocity distribution over each range gate distance, since these frequency
shifts are due to the Doppler effect. Thus, it is possible to gain information on the down-slope velocity distribution within the avalanche at all points for the duration of the avalanche (Schreiber et al., 2001). This information yields valuable insights not just into the global motion of the avalanche, but also its internal structure.

![Image](image1.png)  
*Figure 1.13 – Sites of pulsed Doppler radar. On the left-hand side the radar site R1 with the Austrian radar in place; on the right-hand side NGI's Doppler radar with pre-mounted radar antenna at site R2*

The NGI's Doppler radar uses frequency of about 5.8 GHz, and is mainly sensitive to the denser part of an avalanche. The Austrian radar can switch between 5.8 GHz and 35.8 GHz. The higher frequency allows also resolving the less dense powder part. The use of two frequencies is necessary since electromagnetic waves of different wavelengths interfere differently with the dense-flow and the powder-snow parts of avalanches; one needs a short wavelength (= high frequency) to get reflections from the small snow and ice particles of the powder-snow cloud. The spatial resolution is given by the range-gate size. While the Austrian radar has a minimum range-gate length of 50 m, NGI's radar allows a minimum of 25 m.
2. Instrumentation of dams

2.1 Deflecting dam at Flateyri

2.1.1 General description of the facility

Two 15–20 m high deflecting dams have been constructed above the village of Flateyri, in NW Iceland (Figures 2.1 and 2.2). The dams were constructed after the catastrophic avalanche of 26 October 1995, when 20 people were killed (Figure 2.3).
Both dams have since been hit by moderately large avalanches, in each case with a volume over 100,000 m$^3$ and an estimated return period of 10–30 years (Jóhannesson, 2001). These avalanches hit the dams, which have deflecting angles between 20 and 25°, and ran up the dams 12–13 m. In both cases, the impact with the dam channelised a part of or the whole of the width of each avalanche into a 20–80 m wide stream. The run-out of the streams is estimated to have been increased by over 100 m by the channelisation of the avalanche.

The dams at Flateyri provide a unique location for direct observations of avalanches that hit deflecting dams. The avalanches that have so far hit the deflecting dams are much smaller than the design avalanches of the dams. They have, nevertheless, provided avalanche professionals and the public in Iceland with much welcomed direct evidence of the effectiveness of the dams at Flateyri.

2.1.2 Instrumentation work carried out during the project

Until 2004 there were no permanently installed instruments to monitor avalanche flow at Flateyri. Instead, avalanche events were studied indirectly by measuring the thickness and extent of deposits and looking at the run-up heights on the dams. Figure 2.4 gives an example of the measurements that have been carried out at Flateyri. It shows the run-up of avalanches in 1999 and 2000 on the eastern and western dams.
A microwave CW Doppler radar from the company AlpuG in Switzerland was installed on the eastern branch of the Flateyri deflecting dam in October 2004. The radar is designed to measure the speed of snow avalanches. It was temporarily installed at the Ryggfonn experimental site in Norway (see §1) during the winters 2002/2003 and 2003/2004. The radar was tested at Ryggfonn in controlled experiments before it was installed in Iceland. The two radar antennas at Flateyri are mounted on 4.5 m high masts on the dam itself. A control unit with a data logger and a communication modem is located in a building in the village below the dams (see Figure 2.5).

A technical description of the radar system is given in AlpuG (2003), including a detailed description of the electronics and the format of data files generated by the system. The radar is designed to measure the speed of avalanches as they hit the deflecting dam below the Skollahvilft gully and flow down along the side of the dam. The upper radar antenna triggers the recording system and measures the speed of the avalanches as they flow out of the opening of the gully at about 200 m a.s.l. The lower antenna registers the speed of the avalanches along the dam. Because of the recent installation of the radar, there is no speed data from it at Flateyri available at present.
2.2 Deflecting/catching dams at Taconnaz

2.2.1 General description of the facility

The Taconnaz avalanche path (Figure 2.6) is located in the middle of the Chamonix Valley, in the French Alps, close to the Mont Blanc (4,807 m a.s.l.), the highest peak in Europe. The mean slope of the path is lower than many avalanche tracks. There are two large starting zones separated by a serac. The upper part of the track runs over a glacier. Lower down the avalanche is confined by high moraine until a depression at 1250 m a.s.l.. There are several settlements (Taconnaz, Vers-le-Nant, La Côte-du-Mont) built on the alluvial fan at approximately 1050 m a.s.l.. At these locations the slope angle is still pronounced (about 9.5°). In 1991 a very large defence system against avalanches was constructed at the Taconnaz site (see Figure 2.7), including 5 different deflecting/catching dams and 14 retarding cones; also eleven “flow-spreading” concrete walls (1.5 m wide, 10 m long and 7 m high) were built at the top of the avalanche stopping area (Rapin et al., 2000).
Figure 2.6 – Outline of the Taconnaz avalanche, from the CLPA (Map of Probable Locations of Avalanches)

Figure 2.7 – Avalanche defence systems in the runout zone of the Taconnaz path
2.2.2 Instrumentation work carried out during the project

Two sensors dedicated to measuring avalanche forces were designed and installed at two different heights on one of the eleven “flow-spreading” walls (located in the upper row, on the main avalanche track, see Figure 2.8). Each sensor measures the three components of the force applied by the avalanche flow (see Figure 2.9). The data are recorded on a data logger (Campbell) at 50 Hz for each channel (see Figure 2.10).

Figure 2.8 – View of defence walls where pressure sensors were installed

Figure 2.9 – View of sensor components (left) and the installed sensor (right)

Figure 2.10 – Data loggers
3 Instrumentation of chutes

3.1 Instrumentation of the snow chute at Col du Lac Blanc

3.1.1 General description of the facility

The goal was to build a “laboratory” type of experiment, which would be reproducible and easy to operate, but located high enough so that fresh snow would be easily available and not. For this end, a chute was built near the Alpe d'Huez ski resort, France (Naaim et al., 2001).

The cohesive nature of snow forced us to have a motorised feeding system for the flow. We were afraid that, if one stocked snow in a hopper and just opened it, the cohesion due to sintering would prevent the snow from flowing. Therefore, we designed a feeding system which consists of a storage hopper with an Archimede's screw (see Figure 3.1). The feeding system is commonly used in industry and is known to provide a constant flow rate. The screw is 4 m long and its diameter is 60 cm. It has a slightly increasing step to avoid compaction of the snow while it is carried out. It is set into motion with a diesel engine linked to the screw by a hydraulic engine. This enables us to set a constant rate at any value below 220 m$^3$/h. Since the storage capacity of the hopper is around 5 m$^3$, the flow can last from one to several minutes. However, to avoid excessive compaction of the snow, the hopper is filled up only to one half of its capacity, leading to flows usually of about 20–30 s. The flow channel is sitting on a beam whose inclination is adjustable. Therefore, the slope of the channel can be set from 27° to 45° in steps of 2°. The channel length is 10 m, its width 20 cm and its height 20 cm. Since it is narrower than the screw, a funnel-shaped slide links the end of the screw to the beginning of the channel. The bottom of the channel has been covered with sand paper to reproduce about the same granularity as snow. Underneath, it has a double bottom where the electronic systems required for the sensors are installed. See Figure 3.2 for a schematic representation.

The sensors included in the channel measure: (i) the flow height, (ii) the normal and shear stresses at the bottom of the flow and (iii) the velocities inside the flow (from which the velocity profile is obtained). From these measurements we may derive (i) the effective friction coefficient, defined as the ratio of the shear and normal stresses and (ii) the mean density of the flow. A necessary criterion for the choice of the sensors was that they should be able to work under alpine temperature and humidity conditions.
To measure the flow height we use three optical distance sensors fixed above the flow, perpendicular to the bed surface. The sensors are LEUZE ODS M/V-5010-600-421, recalibrated to perform distance measurements from 100 mm to 350 mm. They were mounted 30 cm above the bottom of the channel which covers flow heights from 0 to 20 cm with a precision of 1 mm, which is only slightly bigger than the typical grain size.
To measure stresses (both the normal and shear stresses) we used a bi-component piezoelectric sensor (Kistler 9601A21-2-20) sandwiched between two metal plates whose dimensions are 20 cm × 50 cm. To avoid tilting of the upper plate, it was necessary to use two sensors. The lower plate is fixed to the beam so that it does not move. The upper plate is linked to the lower one only by the sensors. The stresses applied on the upper plate by the flow are therefore transmitted to the piezo-electric sensors that turn them into electric charges. These charges are then transformed into a voltage by the charge amplifiers. This kind of sensor was chosen for it was the only one that could provide the required sensitivity (forces of a few Newton) and allow convenient installation in our channel.

The charge amplifiers contain complex electronic devices that are very sensitive to temperature and humidity conditions. In particular, it is crucial that their temperature remain above 0°C. Therefore, they have to be warmed up before and during the experiments. Moreover, their calibration fluctuates because of the changing humidity. To perform correct measurements, one has to calibrate the system in conditions as close as possible to those of the experiments. We therefore calibrated them just a few seconds before the snow flow was released.

To measure velocities we used the method based on the cross-correlation of two signals obtained by two identical sensors located downstream one from the other. Basically, each velocity sensor is made of two identical optical devices. These devices are very sensitive to the amount of light collected by the phototransistor. Since this amount of light depends on the granularity state of the reflecting surface, the signal obtained is characteristic of the snow pack that reflected the light from the LED to the phototransistor.

3.1.2 Instrumentation work carried out during the project

During the course of the SATSIE project the instrumentation of the Col du Lac Blanc chute was checked and modified in order to obtain better measurements, especially concerning the velocity measurements in the basal layers. In fact, the first velocity profiles that were obtained showed high velocities down to about 1 to 2 cm above the bed. The size of the original sensors was 8 mm, thus too large to allow accurate analysis of this zone. Those data did not allow us to discriminate between a sliding interface and a sheared layer. Therefore new sensors of 4 mm size were developed and installed. The new sensors were tested in the laboratory in order to quantify the influence of the sensor size on the process of determining the velocity using a pair of sensors and correlation techniques. Afterwards, the Col du Lac Blanc chute was equipped with a high-
resolution velocity profile system. The new results allowed accurate analysis of the sheared zone (see Figure 3.3). In particular the obtained velocity profile shows a thin, highly sheared zone with a thickness of about 2 cm, located at the bottom of the flow, and a zone with a much lower shear rate, which makes up the core of the flow. The shear rate in the thin zone near the bottom is around 200 s⁻¹. This is at least ten times higher than the shear rate within the core of the flow.

![Figure 3.3 - Velocity profile obtained at the Col du Lac Blanc snow chute. Note the thin zone of very high shear rate at the bottom and the linearity of the two distinct segments.](image)

### 3.1.2.1 Snow rheometer

In order to determine the constitutive equation of the dense flowing snow, Cemagref installed a large concentric-cylinder rheometer at Col du Lac Blanc (see Figure 3.4). This system will serve to characterise the snow properties before the chute experiments. The inter-cylinder distance is 20 cm and the total volume is 0.5 m³. The rotation rate can be varied between 0 and 60 r.p.m.

![Figure 3.4 - The concentric-cylinder rheometer](image)
After the analysis of a series of unsuccessful tests with snow (shear localisation, see Figure 3.5), we applied the following modifications in order to avoid the formation of shear bands as much as possible:
- a lateral load is applied through an inflatable membrane;
- a vertical boundary condition is applied using a lid made of Plexiglas to control the total volume and enable visual observations of the experiment.

Figure 3.5 – First tests with snow: shear bands appear near the inner cylinder

3.2 Instrumentation of granular chutes at University of Pavia

3.2.1 General description of the facility

Three different chutes, in the following referred to as chute A, chute B and chute C, are available at the hydraulics laboratory of the University of Pavia for experimental studies with granular materials.

The "Chute A" has rectangular shape and is 35 cm wide and 6 m long, with a constant slope which can vary from 0° up to about 45° (see Figure 3.6 and 3.7). The bed of the channel is metallic and the lateral walls (50 cm high) are made of Plexiglas. A pneumatic gate is installed at the beginning of the channel. The reservoir is 0.8 m long, has a volume of about 0.15 m³, and must be loaded manually. In addition to the metallic bed, in order to vary the frictional properties of the sliding surface, two rough surfaces are available: one made rough by gluing a layer of particles onto a board and the other using sand paper (n°60).
The chute B (see Figure 3.8) is 10.38 m long and 30 cm wide. The lateral walls are 30 cm high. It consists of two Plexiglas reaches: the first is 5 m long and the second is 5.38 m long. The two reaches can be adjusted to different slopes. This channel is mainly employed to study flow-regime transition related to slope changes.
During the SATSIE project also a new chute has been constructed (in the following referred as to chute C), specifically designed for the investigation to be carried out in this project. The chute is completely made of Plexiglas and is self-supporting, has rectangular shape and is 10 cm wide and 30 cm high (see Figure 3.9). The total length is 6 m, including 1 m of reservoir. The release mechanism consists of a gate that slides in two runners milled in the chute walls, a partial opening of the gate allows a constant flow rate of granular material for some seconds. The chute is installed on a three-floor scaffold; the slope is easily variable from horizontal to steeper than 45°.

3.2.2 Instrumentation work carried out during the project

3.2.2.1 High-speed digital cameras

During the SATSIE project a low-cost image acquisition system based on high-speed recording has been built up in co-operation with the Department of Computer Engineering and Systems Science of the University of Pavia. The system has a frame rate higher than usual analogue cameras, but at a comparable cost. This goal was achieved by using off-the-shelf components and avoiding, whenever possible, special purpose parts that would raise the cost of the system significantly. Moreover, all the software had to be open-source so it was easily adaptable to our needs and carried no direct additional costs.

The heart of the system is an advanced camera with digital interface made by Pulnix. It is capable of a sustained rate of 30 million pixels per second that may be arranged into different frame-rates (Figure 3.10). The camera has an electronic shutter able to manage
exposure times from 60 s\(^{-1}\) up to 32,000 s\(^{-1}\). At the moment three cameras are available that can operate simultaneously and are synchronised by a triggering system.

![Image](image.png)

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<td>Full height</td>
<td>640</td>
<td>480</td>
</tr>
<tr>
<td>Half height</td>
<td>640</td>
<td>198</td>
</tr>
<tr>
<td>Quarter height</td>
<td>640</td>
<td>100</td>
</tr>
</tbody>
</table>

**Figure 3.10** – Pulnix TM-6710: image sizes and frame rates available.

Different image processing tools have been developed and tested in order to study the main characteristics of granular flow such as flow height, velocity and concentration profiles, particle trajectories, and erosion processes (Barbolini et al., in press).

*Concentration profiles*

A method for concentration profile estimation from digital images has been developed. This is a histogram-based method that calculates the number of particles using a relation between the gray-level frequencies of the image. As an example, Figure 3.11a shows the grabbed image, Figure 3.11b the result of the processing, used for the estimation of the concentration profile, that isolates the closest particles, and in Figure 3.11c the resulting profile. In order to reduce perspective effects and the impact of optical aberration only the central area of each frame is processed. Indeed, the comparison between processed and normal images (circle in Figure 3.11b) gives a real-time visual control of the threshold level accuracy. This method has been applied to a large number of recordings with different lighting conditions, and has been validated extensively by means of manual concentration measurements. Furthermore, using the measured velocity profiles (see below), the flow rate has been calculated in order to verify the conservation of mass.
Velocity profiles

A method for obtaining one-dimensional velocity profiles, based on pattern matching, has been developed. Consecutive images are taken and divided into interrogation regions (lines) a pixel in height; then every region in the first image is compared with the corresponding region in the second image, trying to identify a displacement $s$ of the pattern. This means that, for every possible overlap of the regions, we calculate the sum of the squared differences between them, looking for the position where the windows are the “least unlike”. In this way it is possible to measure the time evolution of the velocity profile of a granular flow (see Figure 3.12).

A few ways to compute two-dimensional velocity fields based on cross-correlations have been tested (Biancardi et al. 2005). We used correlation-based optical flow and classical particle image velocimetry (PIV), see Figure 3.12, and methods that work by tracking single particles or features along their trajectories, such as feature-based optical flow and particle tracking velocimetry (PTV). Those methods can be utilised only when the displacement of the particles between frames is clearly smaller than one particle diameter, otherwise it is necessary to use the one-dimensional method.
Erosion mechanism

High-speed recording enabled also the study of erosion-deposition processes. An automatic method to single out the particles of the erodible layer set in motion by the main flow, that is to track the erosion front, was set up. The procedure for the image processing can be summarised as follow:

(i) a brightness normalisation in order to reduce the effect of lamp frequency;
(ii) a pixel-wise subtraction between consecutive frames, to highlight the pixels that undergo a brightness variation that is indicative of a particle displacement;
(iii) the application of a “threshold” to filter insignificant variations that only introduce noise into the results.
The developed procedure gives as its final result a black-and-white image, where the white pixels represent the particles in motion (see Figure 3.14). In this way it is possible to trace, automatically for each frame, a line that separates the motionless beads from the others (see Figure 3.14), that is the erosion front. This process is able to recognise displacements even of a single pixel, corresponding to half a particle diameter.

![Flow direction](image)

**Figure 3.14** – Example output of the automatic front-tracking procedure. The white line represents the erosion front

### 3.2.2.2 Other instrumentation

A series of laboratory experiments was recently conducted in chute A in order to investigate impact forces on narrow rectangular and cylindrical obstacles for supercritical granular flow and run-up over deflecting dams (Hauksson et al., submitted). A plate was been added at the end of the chute (Figure 3.15) and dams with different height, slope and deviation angle were mounted on it (Figure 3.16).

The flow depth was measured with an optical distance sensor from Leuze electronic (ODS 96M/D-5020-600-222) that uses infrared light to measure the distance to a surface. It provides a stream of digital distance measurements at a rate of 51 measurements per second, has a resolution of 0.5 mm and a light spot diameter of 10 mm.

Impact forces on obstacles were measured with a DS Europe SERIES 535 QD load gauge. It has a sampling rate of 250 measurements per second, a range of 0–118 N and an accuracy of about ±0.04 N according to the specifications of the manufacturer.
3.2.2.3 *Granular materials*

Different types of granular material have been used according to the phenomena studied. In particular:

- Glass beads (Ballotini®) with mean particle size 90 μm, density 2500 kg m⁻³, bulk density 1500 kg m⁻³;
- High-density polyethylene beads with a mean diameter of 3 mm, density 880 kg m⁻³, bulk density 700 kg m⁻³ and angle of repose 28°;
- PET cylinders with a density of 1280 kg m⁻³, bulk density of 800 kg m⁻³ and angle of repose 30°.
References


Hauksson, S., M. Pagliardi, M. Barbolini and T. Jóhannesson. Laboratory measurements of impact forces of granular flow against mast-like obstacles. Submitted to *Cold Regions Science and Technology* (submitted for EGU 2005 special issue).


