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Development of a remotely controlled debris flow monitoring system in the Dolomites (Acquabona, Italy)

Pia R. Tecca,[1]* Antonio Galgaro,[2] Rinaldo Genevois[2] and Andrea M. Deganutti[1]

[1] *CNR-IRPI, C.so Stati Uniti 4, 35127 Padova, Italy*
[2] *Dipartimento di Geologia, Paleontologia e Geofisica, Via Giotto 1, 35100 Padova, Italy*

Abstract:

Direct measurements of the hydrological conditions for the occurrence of debris flows and of flow behaviour are of the outmost importance for developing effective flow prevention techniques. An automated and remotely controlled monitoring system was installed in Acquabona Creek in the Dolomites, Italian Eastern Alps, where debris flows occur every year. Its present configuration consists of three on-site stations, located in the debris-flow initiation area, in the lower channel and in the retention basin. The monitoring system is equipped with sensors for measuring rainfall, pore-water pressure in the mobile channel bottom, ground vibrations, debris flow depth, total normal stress and fluid pore-pressure at the base of the flow. Three video cameras take motion pictures of the events at the initiation zone, in the lower channel and in the deposition area. Data from the on-site stations are radio-transmitted to an off-site station and stored in a host PC, from where they are telemetrically downloaded and used by the Padova University for the study of debris flows. The efficiency of the sensors and of the whole monitoring system has been verified by the analysis of data collected so far. Examples of these data are presented and briefly discussed. If implemented at the numerous debris-flow sites in the Dolomitic Region, the technology used, derived from the development of this system, will provide civil defence and warn residents of impending debris flows. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS debris flow; monitoring; geophones; ultrasonic sensors; pore pressure transducers

INTRODUCTION

The monitoring and field observation of debris flows, aimed at assessing their physical and dynamic parameters, are very important both for theoretical and practical purposes, such as the determination of their rheological behaviour and the calibration of mathematical models, as well as for planning countermeasures and designing warning systems. Although such physical processes are well described by field observations (e.g. Johnson, 1970; Costa, 1984; Pierson, 1986) and laboratory experiments, both with rheometers (e.g. Phillips and Davies, 1991; Deganutti and Scotton, 1997) and in flumes (e.g. Iverson *et al.*, 1992; Armanini *et al.*, 2000; Egashira *et al.*, 2000), which have led to broadening the knowledge on non-Newtonian flows, direct measurements during natural debris flows (at the field scale) are still scarce because these processes are unpredictable, rapid and highly hazardous.

Automated monitoring systems are needed to collect data on debris flows, but owing to the usually difficult access to debris-flow sites and the high costs of installation, only a few systems are set up around the world. Different types of sensor systems, designed both for debris flow detection and warning, and for specific research purposes, have been installed in Japan (Suwa and Okuda, 1985; Itakura *et al.*, 1997), the Philippines (Marcial *et al.*, 1996), Indonesia (Lavigne *et al.*, 2000), Columbia (LaHusen, 1996), China (Zhang, 1993) and Italy (Arattano *et al.*, 1997; Genevois *et al.*, 2000a).

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* Correspondence to: Pia R. Tecca, CNR-IRPI, C.so Stati Uniti 4, 35127 Padova, Italy. E-mail: pia.tecca@irpi.pd.cnr.it

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There are several quantities concerning debris flows that are of great interest and that have been measured at the field scale by researchers who have dealt with this phenomenon; sometimes specific devices and procedures have been developed for this purpose. Among the most commonly monitored quantities are mean flow front velocity, flow surface velocity, flow depth, mean discharge, triggering rainfall, pore pressure in the initiation zone, total volume, flow unit weight (also commonly called flow density) and impact force.

In 1997 a debris flow monitoring system was installed in the Acquabona channel (Dolomites, Eastern Italian Alps) where events occur every year. Even though the Acquabona debris flow is classified as a hillslope type, according to the definitions by Brunsden (1979) and Costa (1984), the channel is deeply incised in scree. The flows convey coarse, poorly sorted sediment, ranging in size from silt to boulders of over 3 m in diameter.

The Acquabona monitoring system has been established for specific research purposes, aimed mainly at increasing knowledge of the meteorological and hydrogeological conditions leading to debris-flow initiation, the flow parameters and the depositional processes of debris flows. Based on the first 3 years of monitoring activities, in 2000 and 2001 the Acquabona monitoring system was completely redesigned, both in the measuring station structure and in the data acquisition, storing, transmission and management systems. A detailed description of the new Acquabona monitoring system and of its main technical features are provided below and some data are presented in order to verify the effectiveness of single instruments and the quality of the whole system.

STUDY SITE: GEOLOGICAL SETTING, SOIL CHARACTERISTICS AND HISTORICAL DATA

The Acquabona Creek is located on the left side of the Boite River Valley, near Cortina d'Ampezzo, in the Eastern Dolomites, Italy (Figure 1). The upper rock basin is formed of Upper Triassic to Lower Jurassic massive dolomite and limestone cliffs and has a drainage area of 0·3 km^2. The maximum rock basin elevation is 2667 m a.s.l. and its average slope is 43°.

A thick talus covers the slope from the base of the rock-cliffs to the valley bottom; it consists of poorly sorted debris containing boulders up to 3–4 m in diameter and includes heterogeneous scree, alluvium and debris-flow deposits and has a thickness of 40 m at least in the lower slope, as evidenced by a borehole log.

The channel is deeply incised mostly into the talus, and its depth reaches more than 30 m in the intermediate part. Talus deposits are exposed all along the channel except for a 150 m long reach at an elevation of about 1400 m a.s.l., where stratified red marls of Lower–Middle Triassic age (Raibl Formation) crop out. The channel has an average slope of 18°, ranging from 30° in the initiation area to 7° in the lower channel; the channel length is 1632 m.

In order to contain the debris discharged by the flows and protect the national road at the downstream end of the Acquabona Creek, a retention basin was built at the channel outlet. The artificial embankment, made of the same debris material, is about 4 m high.

Particle-size distributions were carried out on the fraction finer than 20 mm of debris sampled in the initiation area, along the flow channel and in the depositional area (Figure 2). The median grain size is similar ($D_{50} = 2{\cdot}5 - 3{\cdot}0$ mm) in the different sampling locations; differences in the silt and clay fractions content occur between the initiation zone, where the percentage of fines (finer than 0·065 mm) does not exceed 10%, and along the middle channel and the depositional area, where the fines content increases to about 30%, owing to the presence of the red marls cropping out along the middle channel.

The climatic conditions are typical of an Alpine environment. Annual precipitation at Cortina ranges from 900 to 1500 mm. Precipitation occurs as snowfall from November to May. Intense summer thunderstorms are common and provide a maximum to the seasonal precipitation regime.

The Acquabona catchment was chosen as an observation and experimental site because its geomorphological and hydrological conditions are quite typical of other areas in the Dolomites prone to debris flows and because debris flows occur annually, thus providing a good opportunity to collect data directly.

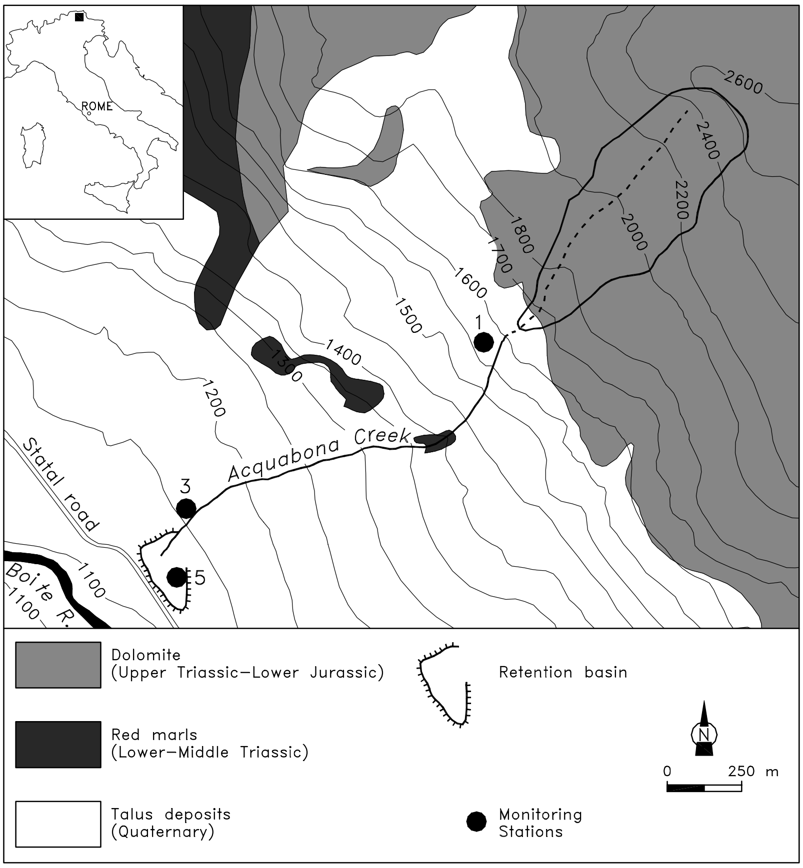

Figure 1. Acquabona catchment: geological sketch and location of monitoring stations

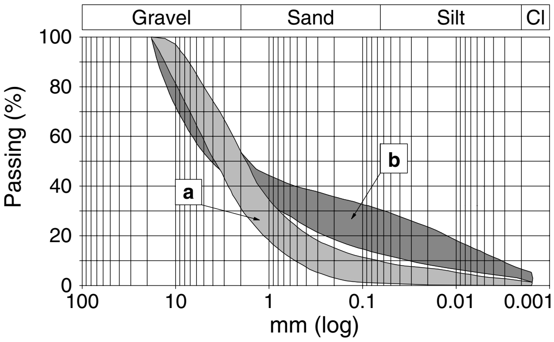

Figure 2. Grain-size distribution of Acquabona debris. (a) initiation area (five samples); (b) flow channel (seven samples) and deposition area (three samples)

Historical information on debris flows that have occurred in the Acquabona catchment has been collected from both public and private sources. Forty-four debris flow events have been found, the first record being September 1882 (Richebuono, 1993), and the most recent on 30 June 2001. Estimation of the magnitude among some of the most recent debris flows in the Acquabona Creek ranges between 500 and 30 000 m^3.

MONITORING SYSTEM

According to the study aims, at the Acquabona site most of the parameters relevant to debris-flow characterization are recorded. The monitoring system is equipped with sensors and instruments for measuring:

1. rainfall and pore pressures in the talus at the initiation zone, in order to investigate the hydrological conditions leading to debris flow initiation—pore pressures are measured either in the channel bed deposits for comparing with the theoretical values as well as in the retention basin in order to investigate the consolidation process of the granular slurry (Major J.J., 2000);
2. flow depth and total normal stress both in the lower channel and in the retention basin, in order to estimate the instantaneous solid discharge and the unit weight;
3. ground vibrations induced by debris flow, to estimate the debris flow front velocity.

Video cameras record images of debris flows both in the upper initiation area, to observe initiation process, as well as in the lower channel reach and in the retention basin in order to obtain particle size and horizontal velocity distributions.

The system is completely automated and remotely controlled, and consists of three on-site stations and an off-site station located 1·3 km from the Acquabona site. The three on-site stations (Figure 1) are located on the right bank of the debris channel; they are identified following odd numbers: station 1 in the debris flow initiation area, station 3 in the lower part of the channel and station 5 in the retention basin.

Operating mode

The system operates in pre-event mode and event mode. During the pre-event mode, data acquisition is continuous and data are sampled every 90 s. This time interval, as any other set-up of the system, can be changed from the remote PCs. When chosen threshold values of geophone signal or rainfall intensity at station 1 are exceeded, the system switches to event-mode and the off-site unit notifies the alarm with a dial call to five different telephone numbers.

The threshold values, the choice of which is crucial for a successful recording of events, have been determined based on past monitoring activities as well as on simulation alarm tests of geophones and rain-gauge sensors. A rainfall intensity value of 4 mm/10 min and an output amplitude of the geophone signal exceeding 400 mV lasting for more than 10 s are the threshold levels chosen for the rain gauge and the acoustic sensor respectively.

In event-mode data are collected at 5 Hz lasting 30 min. After the fast data acquisition, if threshold values are not exceeded for more than 30 min, the data acquisition system turns into pre-event mode. Data are stored at each on-site station in a solid memory and, by remote request, are transmitted to the supervision station; the maximum storage capacity of the on-site flash memory is 150 min.

On-site monitoring stations

Each station consists of a modular low-power system composed of a data acquisition unit, with eight analogue and eight digital inputs, in order to accommodate various instruments and sensors and a radio transmission unit. Solar panels and gel batteries power the on-site stations; electrical transducers are hard-wired to the data acquisition system by electrical cables buried into the debris.

Station 1 (Figure 3A), installed on the right bank of the channel, is equipped with a rain gauge, a geophone, four pore-water sensors and a video-recording system. Station 3 (Figure 3B) is equipped with four geophones, an ultrasonic sensor, a load cell, two pore pressure transducers and a video-recording system. Station 5 (Figure 3C), located in the retention basin at the exit of the channel, includes an ultrasonic sensor, a video-recording system, a shallow pore pressure transducer and a load cell.

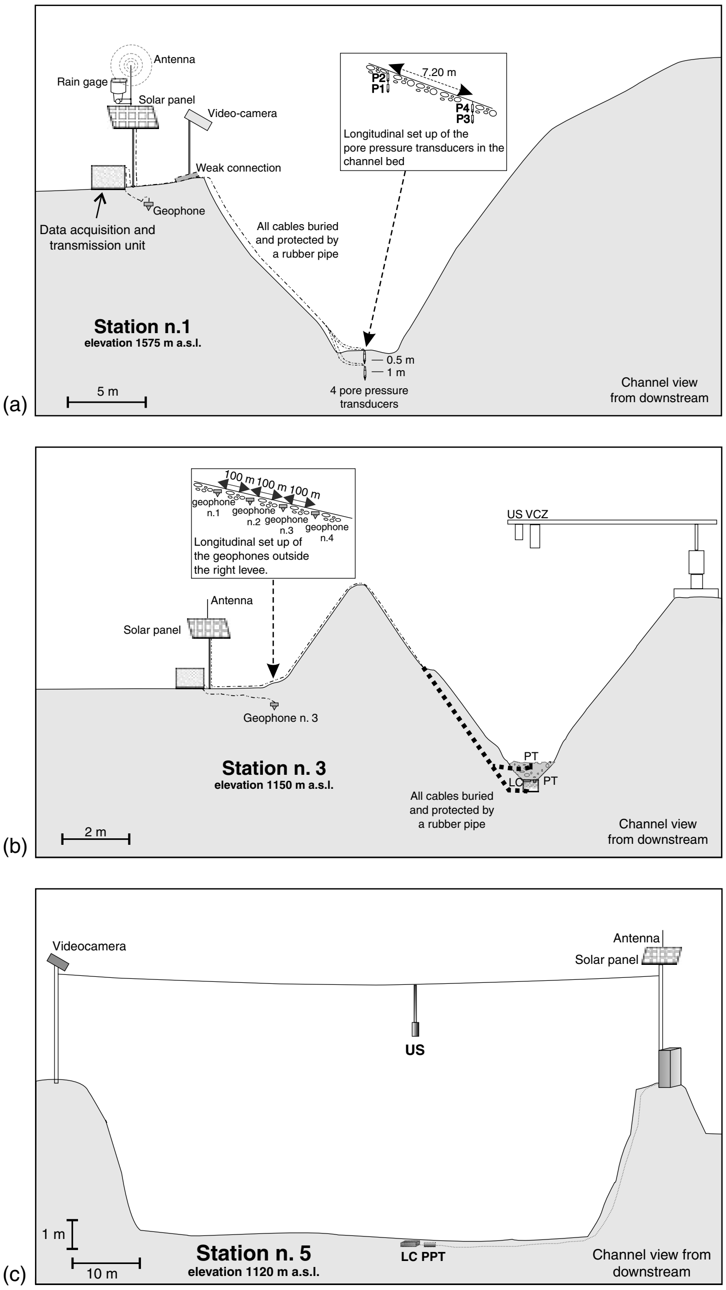

Figure 3. Schematic cross-sections of monitoring stations 1 (A), 3 (B) and 5 (C). VCZ, zenithal videocamera; US, ultrasonic sensor; PT, pore pressure transducer; LC, load cell

Measurement instruments

A rain gauge is positioned in the upper initiation area at station 1. Instantaneous rainfall values are acquired through one of the eight digital inputs of the acquisition unit and computed also as cumulative values.

Pore-water pressures are measured in the initiation area (station 1) by four pressure transducers installed at different depths (Figure 3A): the sensors are placed in two steel rods, 7·2 m apart, at depths of 50 and

100 cm, buried in the loose channel-bed debris, locally 3 m thick, as proved by an excavated pit. This sensor setting is the most suitable to obtain the data required for the hydrodynamic net construction, especially in the conditions leading to debris-flow initiation. Each pore pressure transducer can record pore-water pressure variations ranging between 0 and 100 hPa, with a 0·005 hPa resolution. These four sacrificial sensors function until their cables are severed at a weak connection and they must then be replaced after the event. Two pore pressure transducers are installed at station 3 at depths of 30 cm and 80 cm respectively in the channel bed, in order to measure the pore pressure at the base of the flow during its passage below the ultrasonic sensors. As in this channel section the loose bed might be prone to debris flow scouring, the deepest pore pressure transducer is inserted at the top of a reinforced concrete structure placed at a depth of 2·5 m. The pore pressure transducer of station 5 is 10 cm deep in the debris, inserted in a steel plate buried in the central part of the retention basin.

The monitoring system is provided with induction geophones, sensitive to ground vibrations with a specific frequency of 10 Hz. The flow-induced acoustic waves are measured in order to trigger the fast data acquisition and compute the average front velocity.

Two ultrasonic sensors at stations 3 and 5 measure the flow depth; these sensors have a reading range between 0 and 10 m, with a resolution of 2·5 cm. At station 3 the ultrasonic sensor is suspended over the middle line of the channel from a steel rotating arm (Figure 4). At station 5, owing to the width of the retention basin, the sensor is suspended from a steel cable over the retention basin (Figure 5).

Figure 4. Downstream view of station 3; steel rotating arm with hanging ultrasonic sensor and videocamera in foreground

Figure 5. Downstream view of station 5; solar panel, data acquisition unit, steel cable and suspended ultrasonic sensor in foreground

Two hydraulic load cells measure the total normal stress at the base of the flow during its passage below the ultrasonic sensors at stations 3 and 5. The cells are inserted inside the structures that hold the pore pressure transducers as well.

Three analogue video-systems operate during debris-flow occurrence at a frequency of 25 frames per second. At station 1 the camera, installed on the right bank, frames a panoramic view of the initiation area, whereas at station 3 the camera is suspended above the channel perpendicular to the flow surface, at the same location of the ultrasonic sensor. A third video-system is set at station 5: the camera views the exit of the channel, orthogonal to the flow front. The video-systems are turned on only when rainfall or geophone thresholds are exceeded and the monitoring system switches in event-mode.

Off-site control station

Data acquired at the on-site stations are radiotransmitted at regular intervals to the off-site supervision unit, where they are stored into a PC (Pentium processor, OS Windows NT). The supervision unit is provided with a two-way radio and a radio modem (baud 1200) for communication with the on-site stations. A 56 K analogue modem connects the off-site station with a PC at Padova University, allowing complete remote control of the monitoring system: real-time view of data (both in numeric and graphical form), downloading of data, and change of any set-up of both instruments and thresholds. The station is fed by AC power; it is assured by a 24 V UPS, assisted by two additional batteries of 45 Ah that last for at least 24 h in case of a general blackout.

System management software

The system's management software installed in the off-site station PC operates with the communication protocols and performs several tasks such as the on-site sensors control, the recording of acquired data and data organizing by means of graphical representations. On-site unit management software is installed in an EPROM memory and carries out the following tasks:

1. Cyclic data acquisition by automatic request of the supervision unit. The on-site stations transmit instantaneous and maximum values read by the sensors, as well as voltage values and number of readings.
2. Setting of threshold values of acoustic signal and rainfall intensity for the fast data acquisition trigger.
3. Fast data acquisition every 0·2 s on a memory card when threshold values are exceeded.
4. Activation of the video-recording system after the triggering conditions have been met.
5. Radio transmission of data stored in the memory card to the supervision off-site station.
6. Radio transmission of diagnostic information of on-site stations.

Through the software IDROMATIC 2000 32 bit, the off-site supervision station carries out the following tasks:

1. Data acquisition of the on-site stations with adjustable reading time. Out of scale measurements are also notified.
2. Data processing.
3. Acquisition of logic state variations of sensors, alarm condition check, local alarm set-off and notification by telephone of hazard conditions. Telephone notification is carried out through recorded messages diversified on the basis of hazard level. Telephone notification calls are made to different destinations according to the time and day of week.
4. Real time graphic representation in dynamic synoptic pages for each station, both in graphic and alphanumeric format.
5. Data file export in Excel 2000 or ASCII format, with determination of minimum, mean, maximum and standard deviation values, per hour, day, month or year.

MEASURED DATA AND ESTIMATED FLOW PROPERTIES

As an example of the data collected, measured quantities and some computed flow property data are presented in order to demonstrate the capabilities of such a monitoring system. Data investigate the processes of initiation, propagation and deposition of three events that occurred in Acquabona Creek during the period between summer 1999 and June 2001.

Initiation

Rainfall. The three debris flows considered were generated by high-intensity short-duration rainfalls. In Table I some basic data from the debris flows are presented together with data recorded from previous events.

With regard to the triggering rainfall, the duration (min) represents the interval of time between the beginning of the rain and the onset of the debris flow; the total rainfall is then the amount (mm) of rain within that

Table I. Basic characteristics of recorded debris flows in Acquabona. Total volumes estimated by topographical measurements; velocities calculated by geophone logs

Date	Total volume(m^3)	Triggering rainfall			Mean front velocity range (m/s)
		10 min intensity (mm)	Total (mm)	Duration (min)	
12 June 1997	6000	10·0	25·0	50	3·10–9·00
25 July 1998	600–700	6·0	11·4	90	0·47–0·83
27 July 1998	400–500	6·0	12·4	40	0·77–1·17
17 August 1998	8000–9000	16·0	29·0	58	1·82–7·69
28 July 1999	6000–7000	17·4	37·2	60	
30 September 2000	10 000	4·6	22·4	210	
30 June 2001	30 000	8·6	18·8	120	3·70–4·20

duration. In order to characterize the rainfall event, Table I displays the peak rainfall intensity measured over 10 min.

Pore pressure in the initiation area. The role of rainfall in triggering shallow slope failure has been widely observed and discussed (e.g. Johnson and Sitar, 1990; Iverson *et al.*, 1997). Slope stability conditions are affected, in fact, by changes both in pore-water pressure distribution, owing to the movement of the groundwater, and in shear strength, owing to the increase of the pore pressure itself. Debris flows show to be triggered by short-duration, high-intensity rainfall and some studies indicate that they may result from the development of positive pore pressures accompanying saturation (Reid *et al.*, 1997; Iverson *et al.*, 2000). The transient one-dimensional water flow into unsaturated soils can be solved using the Richard's equation and the method proposed by Lumb (1975) in terms of the depth of the wetting front. Pore-water pressures at various depths thus can be obtained for different rainfall durations and at different vertical sections of the slope, considering, however, that the profiles obtained are affected by specific local boundary conditions. The study of the relationships between rainfall and pore-water pressure changes in shallow soils shows them to be very important. Direct measurements of the rise and propagation of pore pressures as a consequence of rainwater infiltration lead to a better understanding of the following aspects:

1. the actual mechanism of debris destabilization as a transient condition as rain infiltrates, including the progressive failure of the slope;
2. the stress field modifications owing to the rise of pore-water pressures and their distribution being controlled, during rainfall infiltration, by the spatial variation of hydraulic conductivity;
3. the triggering mechanism for conditions where the nature of the failure is or could be gradual and highly transient as rainfall infiltrates.

Figure 6A shows a typical response of the four pore-water pressure transducers at station 1, in the case of no debris flow (Genevois *et al.*, 2000b). The pore pressures increase more or less regularly indicating a continuous rise of temporary groundwater level; furthermore, analysis of the data collected showed that the groundwater flow is characterized by flow-lines dipping 120–140° with respect to the normal to the ground slope. In the case where a debris flow occurs (Figure 6B), pore-water pressures increase almost instantaneously, a little bit earlier on the deepest uphill transducer (P1), thus showing that the advancing water front is almost vertical. The pore-water pressures monitored by the uphill transducers (P1 and P2) seem to indicate the development of flow lines parallel to the slope, a condition that is more critical with respect to the general stability of the slope. The data collected at the two downhill pore pressure transducers are quite difficult to explain: values are similar and, moreover, they keep constant in time. It is our opinion that these values depend on local conditions and, for this reason, we are thinking of a new arrangement of the pore pressure transducers in the triggering area.

Propagation

Front velocity. Recordings of ground vibrations were used to compute the mean front velocity of individual surges along the channel reach at station 3, where four geophones are set up 100 m from each other. As an example, Figure 7 displays the ground vibration logs recorded by geophones 2 and 3. Mean front velocity is calculated from the time interval between the passage of a single debris surge and the distance between the sensors considered. The choice of 100 m as the distance with the acoustic sensors is crucial for the reliability of data: with longer distances, in fact, some of the features of the flow might change owing to local causes (i.e. temporary debris dam, geomorphological channel variations). On the contrary, with shorter distances among the sensors, the temporal cross-correlation between two peaks of the same surge may be difficult to identify.

The distance between the acoustic sensors and the acquisition unit has to be as short as possible in order to avoid high noise levels and dangerous overvoltages, which can occur when the conductor wire is too long. This problem is experienced in high electric impedance soils, such as an unsaturated coarse granular debris.

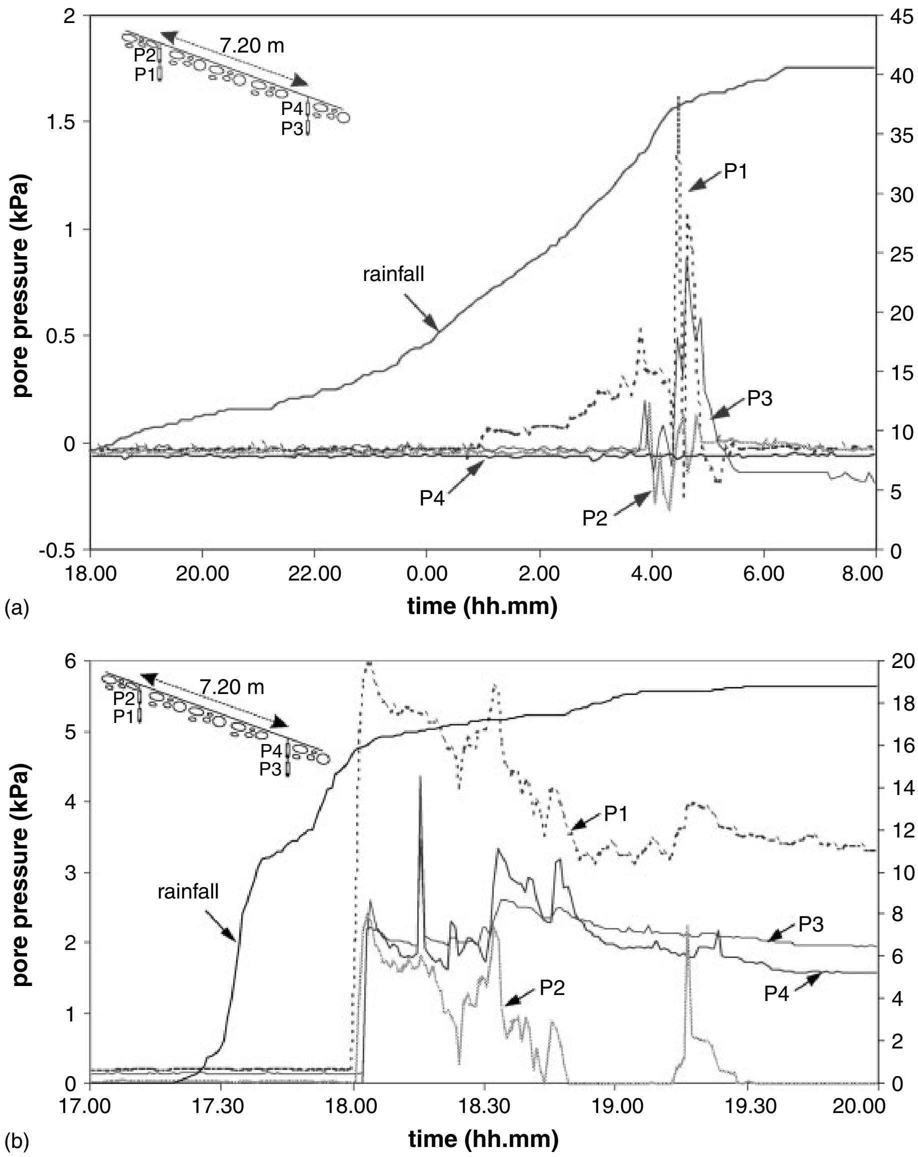

Figure 6. Typical pore pressure response to rainfall at station 1. (a) No debris flow triggering (data recorded on 6 November 2001); (b) debris flow mobilization (data recorded on 30 September 2000). Longitudinal set up of the pore pressure transducers (P1, P2, P3 and P4) is indicated in each figure

Flow depth, basal pore pressure and total normal stress. Hydrographs during the debris-flow propagation are obtained from the ultrasonic sensor at station 3. Some flow characteristics can be evaluated from basal total normal stress and basal pore pressure data in relation to the corresponding values of flow depth (Figure 8). Flow density variations can be estimated from the ratio between total normal stress and flow depth.

With regard to the example in Figure 8, the flow density (flow unit weight) has been estimated between the time interval 300 and 500 s, as after this time the load cell has been damaged by the debris flow. The estimated values of flow unit weight range between 12 and 20 kN/m^3. The liquefaction condition of the slurry can be estimated by comparing total basal normal stress values with basal fluid pressure values (Major,

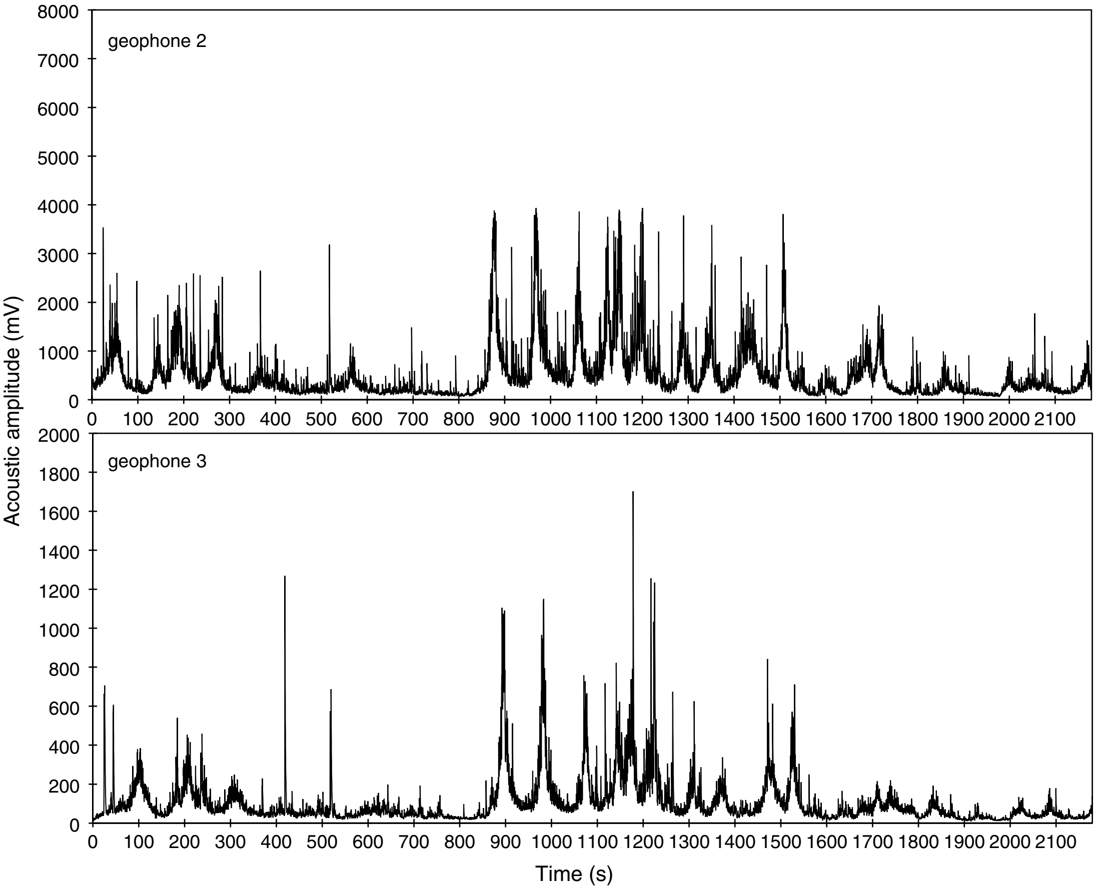

Figure 7. Ground vibrations recorded by geophones 2 and 3 at station 3 during the debris flow on 30 June 2001

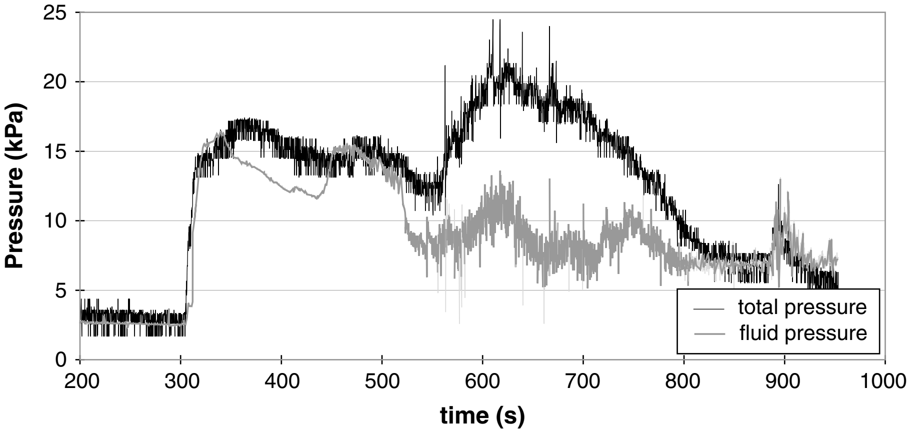

Figure 8. Representative measurements of basal fluid pressure and total basal normal stress during a debris flow (data recorded on 25 July 1998)

2000). The example in Figure 8 shows that pore-fluid pressure is nearly equal to the total basal normal stress during the first 3·5 min: a liquefaction condition of the debris flow slurry persists quite constantly over this period. During the following 5 min the flow slurry is not liquefied any longer, but the total basal normal stress decrease indicates a corresponding decrease of the solid concentration until the slurry turns into a real fluid with a certain amount of suspended particles.

Surface velocity, grain-size distribution and basic rheological parameters of flows. Image analysis techniques applied to video-recordings of flows at Acquabona allow the estimation of both horizontal velocity and grain-size distribution within the flowing material. The analogue images, recorded from the zenithal camera set up along the channel axis, have been converted in digital format. The digital images are then processed to obtain a suitable identification of single flowing particles in order to determine their grain size and track their motion among successive video-frames. Horizontal velocity profiles obtained by video-image analysis are useful to characterize different types of flows: Figure 9A shows a surface velocity distribution typical of a Bingham fluid; a Newtonian fluid, where shear is distributed throughout the cross-section, is represented in Figure 9B.

Some aspects of debris-flow rheology, such as shear strength and viscosity, can be derived from debris-flow depth and horizontal velocity distribution. Total shear strength (K), Bingham (μ_B) and Newtonian (μ_N) viscosities can be computed using the expressions derived from Pierson (1986) and Johnson and Rodine (1984) respectively. Typical values of these parameters, computed for a debris flow recorded at Acquabona, are presented in Table II.

Deposition

The ultrasonic sensor together with the load cell and the pore-fluid pressure transducer set up at station 5, in the retention basin, are utilized in order to investigate the self-loading consolidation process of debris flows in Acquabona. At present we have not collected such data during a debris flow, but the tests performed

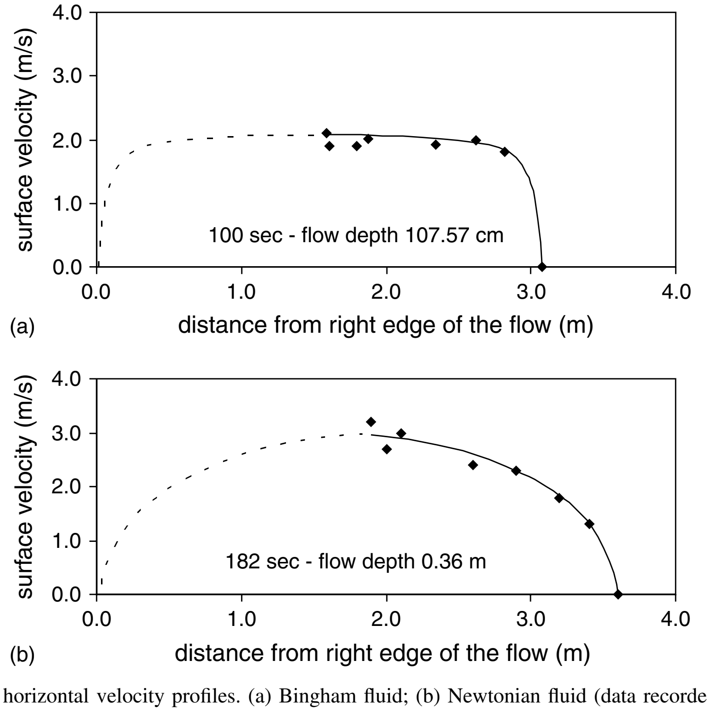

Figure 9. Examples of horizontal velocity profiles. (a) Bingham fluid; (b) Newtonian fluid (data recorded on 17 August 1998)

Table II. Estimated rheological parameters for debris flows at Acquabona. Data refer to the 17 August 1998 event

Time (s)	Flow depth	Surface velocity	Plug width	Flow width	Shear strength	Viscosity (Pa s)	
	d (m)	v_m (m/s)[a]	W_p (m)	W (m)	K (Pa)[b]	Bingham μ_B[c]	Newtonian μ_N[d]
98·80	1·64	2·26	1·79	2·88	1033	76	1214
100·00	1·11	2·08	2·51	3·08	879	14	607
104·60	1·22	2·70	3·04	4·00	840	24	561
108·76	1·16	2·33	2·76	4·41	612	65	590
109·70	1·09	1·90	2·81	3·90	690	38	646
110·00	1·18	2·26	3·01	3·77	864	18	627
111·40	1·04	1·85	3·33	4·47	602	32	593
113·80	1·18	2·50	3·43	3·65	1034	1	569
118·00	0·91	2·72	3·56	4·36	545	9	314
120·10	0·82	2·59	4·01	4·64	457	4	266
182·00	0·36	2·90	—	3·60	0	—	57

[a] Average surface velocity from horizontal velocity profiles estimated from videos.

[b] Pierson, 1986: $K = (W_p/2)\gamma_d \sin S/((W/2d)^2 + 1)$ where γ_d is the unit weight of slurry = 2·0 kN/m^3 and S refers to channel slope at monitoring station 3 (7°).

[c] Johnson and Rodine, 1984: $\mu_B = (KW_p/4v_m)[(W/W_p) - 1]^2$.

[d] Costa, 1984: $\mu_N = (\gamma_d \sin Sd^2)/(2v_m)$.

at station 5 proved that the instruments work correctly during rainfall causing the saturation of debris and the consequent variations of both basal pore-fluid pressure and basal total normal stress.

FINAL REMARKS

A newly developed observation system for the study of debris flows was set up at Acquabona (Italy). The system uses several technologies and instruments for measuring physical parameters of the granular natural soils and the dynamic parameters of the debris flow. The main features of this monitoring system are: (i) small size and low power field data acquisition units, allowing them to be installed high on the steepest channel close to where debris flows form; (ii) it can warn of the occurrence of debris flow by a telemetric network; (iii) two different modes of data acquisition—pre-event mode (low-rate data sampling) and event mode (fast data sampling); (iv) it takes continuous measurements; and (v) it does not require a high level maintenance. The decision parameters of the fast data acquisition trigger are the threshold levels of rain intensity and flow-induced ground vibrations measured in the debris-flow initiation area, and the time during which these values exceed the threshold levels. These values have been determined empirically from data of past debris flows. From these results, the rain gauge was set to a 4 mm/10 min threshold level, and the acoustic sensor at the debris-flow initiation area was set to a 400 mV threshold level, both with a 10 s time duration in the decision circuit.

The Acquabona system is yielding valuable information about the occurrence conditions, flow and depositional stages of debris flows that can be used both for theoretical and practical purposes. New applications of the technology used, derived by the development of this system, if implemented for the numerous debris-flow areas existing in the Dolomitic Region, are expected to provide civil defence and residents with warning of impending debris flows.

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