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Field observations of the June 30, 2001 debris flow at Acquabona (Dolomites, Italy)

Abstract On June 30, 2001, a debris flow occurred in the Acquabona Creek, a small catchment of the Eastern Dolomites, Italy. This debris flow originated shortly after an intense rainstorm, characterised by a peak intensity of 8.6 mm per 10 min; it transported a total volume of 30,000 m^3, consisting of poorly sorted gravely sand with boulders up to 3 m in diameter. The sediment erosion yield rate reached as high as 20 m^3/m. In order to verify the accuracy of the field measurements, the total volume of debris deposits have was calculated using three different topographic measurement techniques: 3D laser scanning, terrestrial stereo-photogrammetry survey and total topographic station survey. Data collected so far show that no debris flow has occurred at Acquabona with a rainfall intensity lower than 4.6 mm per 10 min. Channel cross section measurements indicate that debris flow velocity ranges from 2.0 to 7.2 m/s along the lower flow channel and peak discharge ranges between 22 and 300 m^3/s. Field estimates of the rheological properties indicate a yield strength ranging from 2,088 to 5,313 Pa and Bingham viscosity between 70 and 337 Pa · s. It is not still possible to identify a rainfall intensity and amount threshold for debris flow triggering, but the data so far collected emphasise that debris flows do not occur with a rainfall intensity lower than 4.6 mm per 10 min.

Keywords Debris flow · Precipitation · Physical properties · Rheological properties · Dolomites, Italy

Introduction

Debris flows are highly hazardous hydrological processes common in the Alpine environment. In the Dolomites (northeastern Italy), debris flows generally occur as hillside flows or in channels draining small catchments. Most debris flows occur during the summer following short, localised and high-intensity rainfalls. Channels are often incised in thick talus slopes that provide a large quantity of poorly sorted debris.

Similar conditions for debris flow occurrence on the Alps have been previously observed and described in France (Van Steijn at al. 1988), Switzerland (Rickenmann and Zimmermann 1993; Zimmermann 1990) and in Italy (Berti et al. 1999; Pasuto and Soldati 2004), as they are typical of areas with high relief and intense precipitation. With regard to the channelised debris flows, the initial failure typically involves the loose debris within the channel bed and the flowing mass progressively increases its volume by bed scouring and by sediment contribution from the channel banks. Triggering conditions for this type of debris flows include a critical water discharge caused by intense rainfall and/or a temporary damming of the channel with subsequent failure (Cojean and Staub 1998); however, the relationship between the rainfall and the triggering of debris flows is not simple, depending on a number of factors like the sediment availability and in some cases the antecedent moisture conditions (Deganutti et al. 2000).

In 1997, a debris flow monitoring system was set up along the Acquabona Creek (Eastern Dolomites). This catchment was chosen as an observation and experimental site for its rather high debris flow frequency (events generally occur every year) and because of its geomorphological and hydrological conditions which are fairly typical of other debris-flow-prone areas in the Dolomites.

On June 30, 2001, a debris flow occurred at 21:30. Since there were some maintenance works in progress on the monitoring system, only a few sensors of the system recorded some event data. The flow was triggered by a short-duration high-intensity rainfall. The day after the event, material was sampled for grain size analysis and morphometric measurements were carried out in the channel as well as in the deposition area in order to estimate the flow magnitude. Morphometric measurements were made by means of a topographical total station, terrestrial photogrammetric survey, 3D laser scanner and a laser diastimeter. Aerial recognition of the site completed the data collection with photographs of the fresh deposits.

A description of the June 30, 2001 debris flow and the data collected are presented in this paper. Furthermore, the 3D laser scanner technology will be briefly described, as it proved to be a very useful tool in producing a fast and precise topographical survey of the involved area.

Study site

The Acquabona Creek is located on the left side of the Boite River valley, near Cortina d'Ampezzo, in the Eastern Dolomites, Italy (Fig. 1). The upper rock basin is formed of Upper Triassic to Lower Jurassic massive lightly fractured dolomite cliffs, not affected by karst phenomena. It is considered closed at the channel onset, including only the effective area (0.3 km^2) contributing with water inflow to the debris flow initiation zone. The maximum basin elevation is 2,667 m above sea level (asl) 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 develops from the base of the rock cliffs (initiation zone) and is deeply incised by debris flows 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 the elevation of about 1,400 m asl, where stratified red marls of Lower–Middle Triassic age (Raibl Formation) outcrop. The incised channel has an average slope of 18°, ranging from 30° in the initiation area to 7° in the lower channel; the total channel length is 1,632 m.

In order to contain the debris flows and to protect the national road lying downstream the Acquabona Creek, a deposition basin

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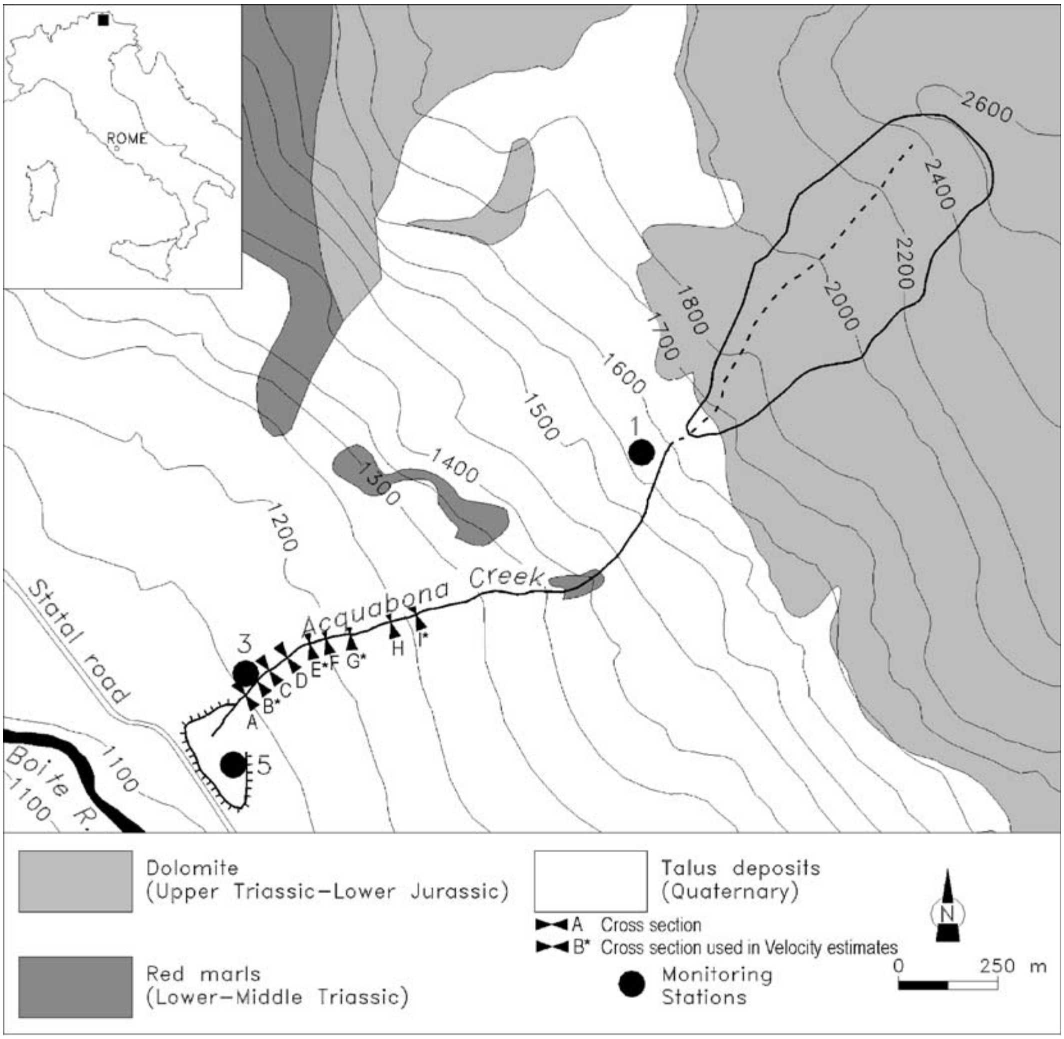

Fig. 1 Acquabona catchment: geological sketch with locations of monitoring stations and surveyed cross sections

was built at the channel outlet. This basin has a maximum width of 110 m and minimum width of 70 m, and its surface slope is about 3°; the artificial embankment, made of the same material transported by the debris flows, is about 4 m high.

Particle size distributions were carried out after the event on the fraction finer than 20 mm of debris sampled in the initiation area, along the channel and in the deposition area (Fig. 2). The grain size distribution is similar (D_{50}=2.5–3.0 mm) for the different sampling locations; differences in the silt and clay content are displayed between the initiation zone, where the percentage of fines (smaller than 0.065 mm) does not exceed 10%, and along the middle channel and the deposition area, where the fines content reaches about 30%. This enrichment in the fine fraction is due to the presence of the red marls outcrop along the middle channel.

The climatic conditions are typical of the Alpine environment. Annual precipitation at Cortina ranges from 900 to 1,500 mm. Precipitation occurs as snowfall from November to May. Intense summer thunderstorms are common; maximum rainfall intensity occurs in summer.

The monitoring system consists of three on-site stations, located in the debris flow initiation area, in the lower channel and in the retention basin, and of an off-site station, which receives and stores data in a host PC. The system is equipped with sensors for measuring rainfall, pore pressures in the talus in the initiation area, ground vibrations, debris flow depth, total normal stress and fluid pore pressure at the base of the flow in the lower channel, as well as in the retention basin. Three video cameras record images of the events in the initiation zone, in the lower channel and in the deposition area.

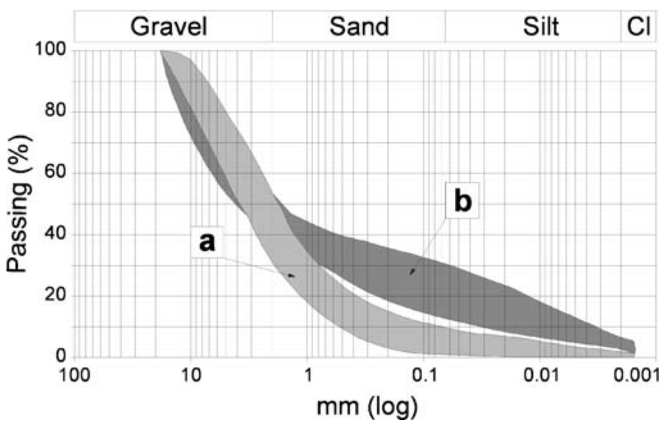

Fig. 2 Grain-size distribution of Acquabona debris. *a* Initiation area; *b* flow channel and deposition area

The June 30, 2001 debris flow event

Direct observations

On June 30, 2001, at 21:30, a debris flow occurred in the Acquabona channel after an intense and localised thunderstorm. Owing to the darkness, the recorded video of the flow was not suitable for the analysis. The following is a description of the event as directly observed in the field and from the aerial photographic survey carried out the day after the event.

The water collected in the rock basin reached the initiation zone through a narrow rocky incision that delivered it straight to the onset of the flow channel, where a large amount of loose debris had accumulated in the deep gully. The debris flow initiated immediately downstream of a boulder field, at 1,590 m asl (Fig. 3), that separates the debris channel downstream from the rocky incision upstream. No evidence of bank failures was detected in the initiation area and only the channel bed debris was mobilised. The volume initially mobilised has been estimated on the basis of field investigations. In the initiation area, the thickness of the loose channel bed debris ranges between 1.5 and 2.5 m.

Assuming a trapezoidal shape of the channel section and an average 30-m channel reach contributing to the initiation area, an initial volume of 300–400 m^3 of debris has been estimated. Along the channel, the flow mobilised mainly the loose debris of the channel bed; no significant contribution came from bank erosion, although debris falls and small slumps from the right channel bank occurred just below the red marls outcrop, in the middle channel reach. Debris flow traces and deposits along the channel were surveyed. Erosion processes were observed along the first 1,000 m of the channel below the initiation area: channel bed scouring was up to 1 m in the upper course (between 1,650 and 1,370 m asl), while along the lower reach the channel bed deepened approximately 20–30 cm.

Lateral levees, overbank deposits (0.8 to 1.5 m of thickness) and channel bed deposition have been observed below 1,200 m asl. Fresh mud marks on banks recorded flow depths up to 3.6 m, between 1,260 and 1,180 m asl. Boulders with dimensions up to 3.5 m were found in the lower channel reach and in the deposition area (Fig. 4a, b).

The flowing mass cut through the right channel bank 50 m upstream the retention basin (Fig. 5) spreading out on to the lower slope, as well as overflowing into a spillway on the left side of the embankment, clogging the pipe (diameter is 1.8 m) that passes under the national road, spreading on it and reaching the Boite River about 50 m below, over a distance of 180 m. The terminal deposit in the retention basin was about 50 m wide and 110 m long with a slope of 5–7°, having a thickness ranging from 3 to 4 m.

Analysis of the debris flow event: topographic measurement techniques and volume estimations

The event had a duration of about 45 min, as recorded from the monitoring system. Tecca et al. (2003) provide a detailed description of the Acquabona monitoring system.

The total volume of the debris deposit was estimated by comparison of contour line maps obtained from measurements taken by a total topographic station. The topographic total station includes a tacheometer, an optical prism and an infrared diastimeter. The station provides zenith and bearing measurements and distances from the operator and the optical prism locations. A contour line map before the event was already available from previous field measurements.

After the event, the debris almost entirely filled the retention basin; a new topographic survey was performed on the terminal deposits and the debris flow volume, determined by difference of the two topographic surfaces (before and after the event), was estimated in about 30,000 m^3.

The topographic surveys were also carried out using two other techniques: the 3D laser scanning and the terrestrial stereo-photogrammetry survey in order to verify the accuracy of field measurements.

Fig. 3 View of the initiation area. Onset of the channel incised in the talus

Fig. 4 Large boulders in the lower channel reach (**a**) and in the retention basin (**b**)

Fig. 5 Aerial view of the retention basin cut

The 3D laser scanner includes a laser source, a laser signal receiver and a pointing video camera, managed by a specific software resident on a laptop PC. The instrument frames a view of ±40° and acquires 800 points per second; the maximum reading distance is 100 m with an accuracy of 1.5 mm. The advantage of this technique is that only one person is required to take the measurements. The backscattering data can be interpreted to retrieve information about the texture and moisture content of the slope.

The laser survey was carried out in the retention basin before the described event in order to acquire, in 3D form, morphological and topographical features of debris flow deposits with a spatial resolution of 7 cm. The feature of this kind of survey is that each scanned image is composed of 3D points; the final output can be a contour line map of the surveyed area. The deposited volume, determined by the difference of the two laser survey topographic maps (before and after the event), was estimated to be about 30,500 m^3.

Terrestrial stereo-photographs are taken from fixed positions by a 50-mm reflex camera; topographical markers, set up on the ground surface in the retention basin, geo-refer the survey. The survey carried out after the event provided a contour line map that, compared with the pre-event ground surface, gave a deposited volume value of about 28,000 m^3.

A comparison of the estimated volumes show differences, with respect to the value obtained from the total topographic station, of 1.6% and 6.6% for the 3D laser scanner and the terrestrial stereo-photogrammetry survey, respectively.

Along the channel, the flow incorporated debris at a rate of approximately 18 m^3/m, determined from the total volume of the deposited debris (30,000 m^3) minus the estimated volume of the material mobilised from the source area (300–400 m^3) and averaged over the channel length (1,645 m). Similar values (15–30 m^3/m) were obtained by Hungr et al. (1984) for catchments of similar morphology, geology and hydrological conditions. Previously estimated sediment yield rates at Acquabona, based on events of 1992 and 1997, were 5–6 m^3/m (Marchi and Tecca 1996; Berti et al. 1999). The calculated value of 18 m^3/m should be considered an estimate because field surveys showed evidence of channel bed scouring as well as a certain amount of debris lateral deposits impossible to estimate.

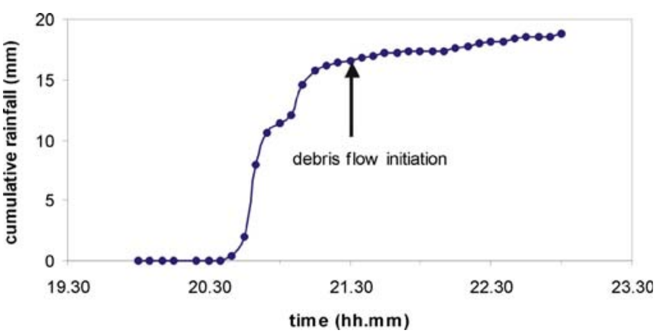

Fig. 6 The cumulative rainfall of 30 June 2001

Rainfall and water discharge

The rainfall that triggered the event was characterised by a peak intensity of 8.6 mm per 10 min, a total amount of 16.2 mm and a duration of 55 min. Total amount and duration are considered from the beginning of the rainfall until the onset of the debris flow. Figure 6 displays the cumulative rainfall of 30 June 2001: the initial debris surge was recorded approximately 35 min after the peak rainfall intensity. This fact was also observed in Japan (Suwa and Okuda 1985) and in Acquabona during debris flows occurring in 1997 and 1998 (Berti et al. 1999). Table 1 displays basic data of the debris flows recorded during the period 1997–2001, as well as rainfall not followed by a debris flow event. The average slope gradient of the upper rock basin is very high (around 43°) and colluvium is limited to a few small areas with a lower gradient. Such characteristics determine a quick hydrological response, as confirmed by the rapid pore pressure increase associated to the rainfall recorded in the initiation area. Figure 7 shows an example of a typical diagram of rainfall and pore pressures, related to the event of 30 September 2000. Lacking direct measurements and because the site is not suitable for the installation of a discharge flowmeter, an estimate of the water inflow at the initiation area of the debris flow has been made using the rational method:

$$Q = \frac{k\,C\,h_c\,A}{t_c}$$

where k is a conversion factor; C is the runoff coefficient; h_c is the amount of rainfall (mm) in the concentration time t_c (h), and A (km^2) is the rock basin area.

The application of the rational method can be considered reasonably reliable because the upper rock basin that feeds the debris flow channel has a limited extension and a very high slope gradient. Furthermore, it is almost entirely constituted by lightly fractured dolomite and not affected by karst phenomena. Such characteristics determine a quick hydrological response as confirmed by direct observations (Berti et al. 1999) and a limited influence of antecedent precipitation.

The concentration time has been estimated by two different empirical formulae, both suitable for steep mountain catchments:

$$t_c = \frac{(4\,A\,0.5 + 1.5L)}{0.8(H_{\mathrm{m}} - H_{\mathrm{o}})^{0.5}}$$

$$t_c = \left(\frac{0.396\,L}{i^{0.5}}\right) \cdot \left(\frac{A}{L}\sqrt{\frac{i}{i_v}}\right)^{0.72}$$

where L is the headwater basin length; H_{m} is the average basin elevation; H_{o} is the rock basin outlet elevation; i is the average channel gradient, and i_{v} is the average slope gradient. The morphometric parameters used in the calculation are listed in Table 2. The estimated concentration times are 14 and 9.5 min,

Table 1 Main characteristics of 1997–2001 debris flows and rainfalls recorded at Acquabona

Date	Hour	Total volume (m^3)	Rainfall			Mean front velocity range (m/s)	Peak water discharge (m^3/s)	Total water inflow at initiation area (m^3)
			10-min intensity (mm)	Total (mm)	Duration (min)			
12 Dec. 1997	15:30	6,000	10	23.8	55	3.1–9.0[a]	4.02	7,140
14 Jul. 1997	–	–	13	40	50			
25 Jul. 1998	20:10	600–700	4.9	8.1	35	0.47–0.83	1.97	2,430
27 Jul. 1998	20:20	400–500	5.8	12.5	40	0.77–1.17	2.33	3,750
17 Aug. 1998	20:15	8,000–9,000	14.7	22.35	55	1.82–7.69	5.91	8,760
28 Jul. 1999	15:30	6,000–7,000	17.4	46.2	105		6.99	14,220
23 Jun. 2000	–	–	5.0	9.8	60			
28 Jul. 2000	–	–	3.6	11.8	90			
5 Aug. 2000	–	–	3.6	14.8	90			
17 Aug. 2000	–	–	13.2	19	70			
30 Sep. 2000	18:10	10,000	4.6	16.4	50		3.49	4,935
6 Jun. 2001	–	–	1.6	11	270			
30 Jun. 01	21:30	30,000	8.6	16.6	55	2.0–7.2[a]	3.45	5,000

[a] Mean velocity estimated by superelevation of flow on channel bends

respectively, for the two methods. Considering an average concentration time of 12 min, a conversion factor (k) of 0.278 and a runoff coefficient of 0.8, suitable for the poorly fractured rock of the upper basin, the water inflow to the debris flow initiation area results 3.45 m^3/s. The total volume of the water inflow before the debris flow initiated, estimated as the rainfall total amount by the rock basin area, was about 5,000 m^3. The delay between the maximum rainfall intensity over 10 min and the debris flow initiation corresponds to the time required to saturate the loose debris that fills the channel in the initiation area. Such material has a very open structure with a thickness around a few metres and rests on less permeable slope deposits: water coming from upstream circulates preferentially in the surficial debris layer and eventually flows above the surface, if its capacity is exceeded.

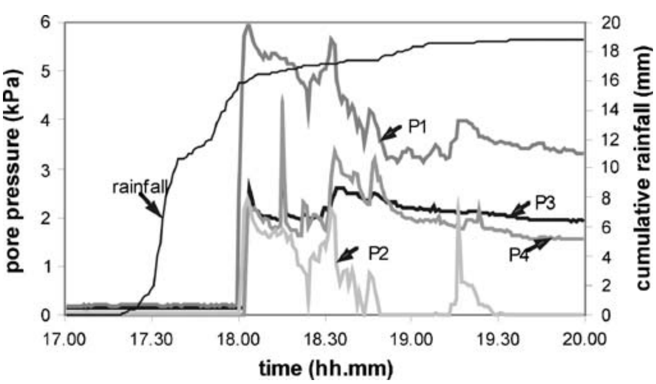

Fig. 7 Typical pore pressure response to rainfall in the initiation area (*P1* and *P3*: 1.0 m deep; *P2* and *P4*: 0.5 m deep)

Debris flow velocity and field estimation of rheological parameters

The on-site stations were affected by induced currents caused by the rainstorm that generated a dysfunction of the monitoring system. Average debris flow velocities have been estimated by the superelevation of flow around the channel bends. After the event, nine channel sections were surveyed, measuring the thickness and surface slope of overbank deposits and measuring superelevation of mud lines, channel centreline curvature and channel cross-sectional geometry at the bends (Fig. 1).

Following Johnson (1984), for channel slope less than 15°, the mean velocity of the debris flow (v) at bend sections can be estimated from:

$$v^2 = g\,\psi \tan\beta$$

where g is the acceleration due to gravity; ψ is radius of curvature; $\tan\beta$ is $\Delta h/W$; Δh is the elevation difference between the flow surface on the inside and outside of the bend, and W is the flow width.

Average velocity and peak solid discharge values, estimated as the product of average velocity by the flow cross section area (A), are reported in Table 3.

Although the applicability of the Bingham model to natural debris flows has been questioned, there is experimental evidence that the muddy–sandy slurries transporting coarse clasts at Acquabona behave approximately as Bingham fluids (Genevois et al. 2001). Debris flow viscosity has been calculated through cross sections, given field estimates of yield strength, channel slope, bulk density

Table 2 Morphometric parameters of the rock basin

A (km^2)	H_m (m)	H_o (m)	L (km)	I	i_v
0.3	2,158	1,650	1.3	0.78	0.96

and plug velocity. Since the flow was not recorded by the monitoring system, flow hydraulics had to be reconstructed from the mud lines. Field mapping established nine cross sections sufficiently well preserved to allow a reconstruction of flow hydraulics (Fig. 1).

If the Bingham constitutive equation is used to model the flow, the appropriate value of strength is that one related to the ultimate cessation of flow. The more reasonable method of field estimation is then based on overbank deposit thickness (h) and its slope (S). The mean basal stress, at the time of deposition, was approximately equal to the yield strength (Johnson 1984):

$$\tau = \gamma_d \, h \sin S$$

where γ_d is unit weight of debris. The debris flow unit weight was estimated by sampling the debris mixture half an hour after its deposition in the retention basin. Unit weight ranged from 20.0 to 22.0 kN/m^3.

This equation is reasonably accurate for lobes with width to depth ratio >10. The snouts of overbank lobes deposited on relatively planar surfaces are the most suitable for yield strength estimation; thicknesses measured along the surveyed channel reach varied between 0.8 and 1.5 m.

Estimates of yield strength range from 2,088 to 5,313 Pa (Table 3).

Flow viscosity was estimated at four representative cross sections of a straight channel reach, located between two surveyed bends, because they provide the closest approximation to the conditions of steady rectilinear flow assumed for a Bingham fluid (Fig. 1). Cross sections were surveyed where no superelevation of mud lines could be detected and where the channel bed had not been significantly deepened by post-debris flow water erosion. Viscosity (μ_B) can be calculated from the average velocity (υ_m) estimated between two surveyed bends, flow width (W), plug width (W_p) and yield strength (K) by applying the relationship (Johnson 1984):

$$\mu_b \left(\frac{K\,W_p}{4\,\upsilon_m}\right)\left[\left(\frac{W}{W_p}\right)-1\right]^2$$

The plug width was assumed to be 78% of the flow width, from experimental data of similar flows at Acquabona (Genevois et al. 2001).

Viscosity estimates range from 70 to 334 Pa · s; because of the overestimation of velocity measurements at bends and a certain error in the field-calculated yield strength, the values are reported as the plausible range for the field data (Table 3).

Conclusions

On June 30, 2001, a large debris flow occurred at the experimental site of Acquabona, Italy. The debris flow was generated by a small initial failure occurring on the loose coarse bed material in the very upper channel; a remarkable degree of channel incision caused the volume increase of the flowing mass along the channel up to 30,000 m^3. The availability of debris material in the upper part of the channel is always assured by accelerated erosional processes, so that this site always contains a large amount of material for innumerable debris flows to occur.

The debris flow was triggered by a total precipitation of 16.6 mm, characterised by an intensity of 8.6 mm per 10 min, comparable with the rainfall intensities associated to past debris flows. During the enhanced surficial infiltration of water, a local saturation zone and the liquefaction of the material occur, either for blockage of groundwater flow paths or for an additional impact of water discharging from the fractures of the rock basin or for the impact of a small debris mass (Sassa 1984). This causes the pore water pressure to build up, reducing the effective internal shear strength.

Most of the debris flowed within the channel; a part overtopped the lower lateral levees spreading on the road to the Boite River below, at a distance of 2,000 m from the initiation zone. High mud marks, which were measured along the channel, were interpreted to represent the flow surface. These estimates of flow level are considered to be maxima since the flow has a certain splash component when travelling along directions different from the channel direction. The flow transported downhill several boulders up to 3.5 m in diameter.

Although no data from the monitoring system were available about the motion of this flow, some important debris flow parameters were determined by using the following methods: topographical measurement techniques (3D laser scanning, terrestrial stereo-photogrammetry, topographic total station survey) and field survey observations of traces of the debris flow (size of large boulders,

Table 3 Hydraulic and rheological parameters of June 30, 2001 debris flow

Cross section	Cross-sectional Area (m^2)	Average velocity (m/s)	Peak solid discharge (m^3/s)	Yield strength (Pa)	Bingham viscosity (Pa · s)
A	11	2.0	22	3,552	264
B[a]	18	2.0	36		
C	24	2.8	67	5,209	307
D	33	2.8	93	5,313	337
E[a]	51	3.7	188		
F	36	4.0	141	2,998	139
G[a]	38	4.2	159		
H	40	5.7	226		
I[a]	41	7.2	299	2,088	70

[a] Cross section on channel bend

erosion, lateral deposits, superelevation around channel bends). Field study brought about the following remarks:

1. The debris flow had velocities of 2.0–7.2 m/s with peak solid discharges of 22–300 m^3/s along the lower channel reach; the event magnitude was 30,000 m^3 and the maximum erosion yield per unit channel length was 18 m^3/m. The above values are comparable with values determined for past debris flows occurring in Acquabona (1999).
2. Some rheological parameters were estimated in the field at well-preserved cross sections; yield strength values range between 2,088 and 5,313 Pa; Bingham viscosity estimates range from 70 to 337 Pa · s. The estimated strength values are quite higher than strength values estimated by Genevois et al. (2001) for the August 1998 debris flow at Acquabona (611 to 850 Pa). This difference is mainly due to the higher flow depth of the June 30, 2001 debris flow. The estimated Bingham viscosity is comparable with viscosity values estimated for the July 1998 debris flow at Acquabona (127 to 178 Pa/s); the higher values of the range are a consequence of higher yield strength values.
3. The analysis of rainfall data associated to debris flow occurrence at Acquabona shows that the meteorological conditions for debris flow initiation vary in a relatively wide range. The time of occurrence of debris flows was between 35 and 105 min after the onset of the rainfall, generally about 30 min after the peak rainfall intensity over 10 min. In this period, the accumulated precipitation varied from about 8 to 46 mm. The peak rainfall intensity was 4.6 to 17.4 mm per 10 min. A comparison with some past rainfall data indicates that rainfall of similar or even higher intensity and larger accumulated precipitations had occurred without a debris flow being initiated. Among others, a 50-min rainfall with peak intensity of 13 mm per 10 min was recorded on July 14, 1997, definitely larger than the precipitation associated to the debris flow of July 27, 1998 (see Table 1). It is not possible to identify a rainfall intensity and the amount threshold for debris flow triggering, but the data so far collected emphasise that debris flows do not occur with a rainfall intensity lower than 4.6 mm per 10 min.
4. Rainfall intensity and the accumulated rain that shortly preceded (no more than 105 min) the debris flows are necessary but not sufficient conditions for debris flows to occur. Sometimes, antecedent rainfall amounts have been recorded, but they do not represent a significant factor for debris flow occurrence because of the high permeability of the coarse deposits in the initiation zone. Rather, the availability of debris in the initiation area is essential for debris flow occurrence, as well as its setting.

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