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Monitoring the propagation of a debris flow along a torrent

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Abstract The results are presented of a field experiment on debris flow monitoring that were obtained in the summer of 1996 in a small mountain torrent in the Italian Alps. A network of seismic detectors was placed about one kilometre upstream of some previously existing gauging stations equipped with ultrasonic devices. In June and July two debris flows occurred, which were recorded both by the seismic and the ultrasonic sensors allowing a comparison between the two results. For the first event, the plot of the mean velocity of ground vibration *vs* time revealed a strong similarity with the hydrograph recorded at the gauging sites: the graphs show the passage of a debris flow wave with a sharp peak followed by subsequent smaller waves. An estimation of the mean front velocity of these waves was performed at both sites.

Enregistrement de la propagation des laves torrentielles dans un cours d'eau

Résumé Les résultats de mesures *in situ* pour l'enregistrement de la propagation des laves torrentielles observées en 1996 sur un cours d'eau des Alpes Italiennes. Un réseau de sismographes a été disposé au bord du lit, 1000 m environ en amont de trois stations de jaugeage hydrométrique par ultrasons. Deux laves torrentielles ont été enregistrées par les sismographes aussi que par les ultrasons, ce qui a permis de comparer les deux systèmes d'enregistrement. Pour la première lave, le graphique des vitesses moyennes de propagation des ondes transmises dans le terrain en fonction du temps a révélé une stricte similitude avec le graphique obtenu par les ultrasons. Les graphiques montrent tout particulièrement que le passage de la lave se caractérise par une onde initiale abrupte, suivie par des ondes de moindre importance. Il a été possible de calculer les vitesses de propagation des ondes aux deux extrémités de la partie de lit équipée.

INTRODUCTION

Several observers have described debris flows as phenomena producing thunderous roars and strong ground vibrations (Johnson & Rodine, 1984; Suwa & Okuda, 1985; Takahashi, 1991). It is also well known that these vibrations, which propagate from the heads of debris flows, precede them so that people living at the lower reaches of debris flow prone torrents can often detect the occurrence of such phenomena, before their arrival, by the vibrations they produce (Okuda *et al.*, 1980).

These observations have suggested a test for some of the instruments usually employed by geophysicists, that is geophones and seismometers, to investigate the vibrations induced by debris flows. Some studies have already employed accelerometers for this purpose (Suwa & Okuda, 1985), others have developed specific

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sensors (Zhang, 1993; Lahusen, 1996; Itakura *et al.*, 1997), while velocimeters and acoustic sensors have also been used for monitoring bed load transport (Banziger & Burch, 1990; Govi *et al.*, 1993). However field data on ground vibrations produced by motion of debris are still scanty worldwide.

The Moscardo Torrent, a small creek located in northeastern Italian Alps (Fig. 1), has been chosen as the investigation site. Typically, two debris flows per year occur in this torrent, usually during the summer season. Three gauging stations equipped with ultrasonic sensors were already installed in the basin, along a straight reach of the torrent on the fan. The first two ultrasonic sensors were installed in 1989 and the third in 1995. Several debris flows had been recorded successfully between 1989 and 1994 (Arattano *et al.*, 1997) and the number of monitoring devices and intensity of investigations in the area were therefore increased. As part of this increased research activity and following the ideas previously exposed, in 1995 a network of seismic sensors was placed on the right channel bank of a straight torrent reach, located about 1 km upstream of the gauging stations, in the middle portion of the basin (Fig. 1). Since there were no means to predict the occurrence of debris flows, the seismic signals were recorded continuously using an analogical magnetic tape recorder.

The purpose in installing seismic sensors in this basin was to verify which information could be obtained through this type of device on the occasion of a debris flow occurrence. In particular, the investigations were directed to verify the existence of a dependence of the seismic signal on flow depth and grain size and to explore the possibility of using seismic sensors as warning systems for debris flows (Arattano, in press).

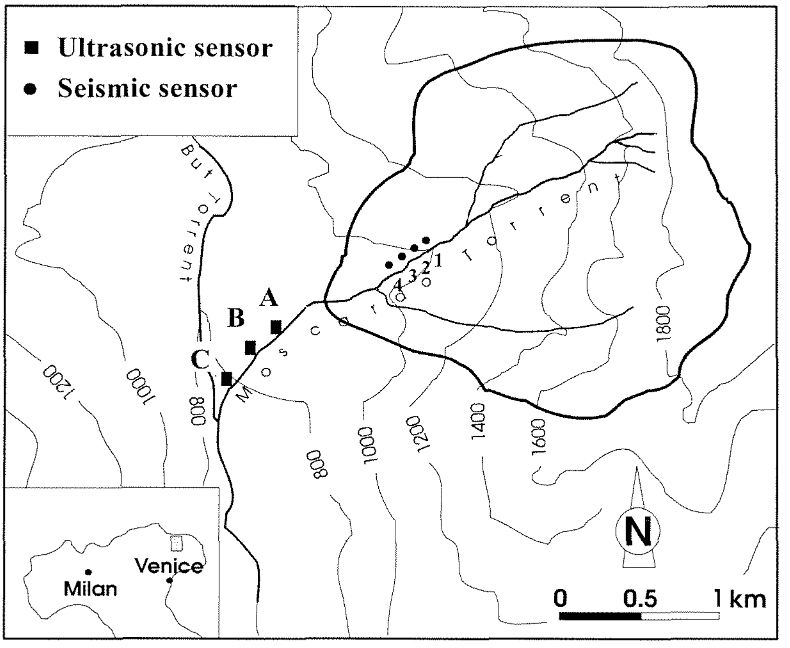

Fig. 1 Geographical location of the Moscardo Torrent. (A, B, C: ultrasonic sensors; 1, 2, 3, 4: pairs of seismic detectors).

STUDY SITE AND INSTALLATIONS

The Moscardo Torrent drains a small basin (4.1 km^2) located in the northeastern Italian Alps (Fig. 1). The rocky substratum of the Moscardo basin is made of shale, slates, siltstone, sandstone and breccia that are exposed throughout the upper portion of the basin and locally along the torrent (Arattano *et al.*, 1997). Trees and shrubs occupy most of the basin surface (64% and 18% respectively), while the remaining portion consists of bare areas, mostly concentrated in the upper basin and partially along the steep side slopes of the torrent, which are subject to frequent landslides. Arattano *et al.* (1997) provide a summary of the main morphological parameters of the basin.

The Moscardo Torrent debris flows usually carry material of very heterogeneous dimensions. Several particle size analyses have been carried out on the matrix of different debris flow samples collected from deposits left on the torrent fan. These analyses show that the particle size of debris flows varies little. The grain size distribution of the deposited material usually ranges from 0.001 mm to 2–3 m (Arattano *et al.*, 1997). The presence of boulders of several cubic metres in volume in the debris flow mixture was considered capable of producing ground vibrations recordable by the seismic detectors placed on the banks of the torrent.

The seismic network, consisting of four pairs of vertical seismic detectors (seismometers and geophones) placed on the ground in an upright position, was set along the right bank of a straight torrent reach located in the lower basin (Fig. 2). The reach has a length of 303 m and a mean slope of 14.9%. As previously mentioned, a gauging station equipped with three ultrasonic sensors is present about 1 km downstream of this site (Fig. 1). The site was selected for its easy accessibility due to the presence of a road used by the Forest Service to inspect one of the several check dams present along the torrent (Fig. 2). The first, upstream pair of detectors was placed close to the check dam, the remaining three along the road that leads to it.

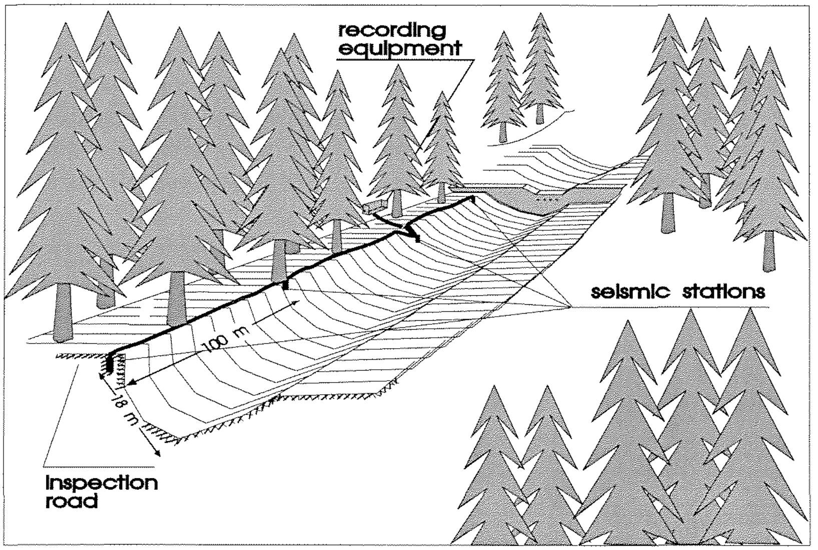

Fig. 2 Sketch of the torrent reach where the seismic detectors are placed and their positions along the reach.

The distance between each pair of seismic sensors was about 100 m (100 m between the first and second pairs, 102 m between the second and the third and 101 m between the third and the fourth). The choice of the distance between the detectors is discussed by Arattano (in press). Each pair of detectors comprised a vertical seismometer (Mark L4C model) with high sensitivity, a transduction constant of 160 V s m^{-1} and a natural frequency of 1 Hz (type 1 sensor); and a geophone (Mark L28B model) with a transduction constant of 40 V s m^{-1} and a natural frequency of 4.5 Hz (type 2 sensor).

The detectors employed were designed to maintain a close frequency tolerance with respect to tilt and temperature, low distortion of signals and for use in the worst environmental situations such as those present at the Moscardo site. The choice of these sensors derived from experience developed in Valtellina (northern Italy) to control the slope stability in Val Pola after the ruinous landslide on 28 July 1987. In that context, a complex monitoring system, including a seismic and acoustic emissions network, was installed to assure the safety of the interventions during the most critical period of hydrogeological emergency (Baldi & Bonaldi, 1987). The results obtained proved that seismometers could record not only the seismic waves generated by earthquakes but also signals with very low amplitude such as rock fall and crack formation (Calvano *et al.*, 1993).

At the Moscardo site the sensors were connected to the recorder unit by shielded cables enclosed in rubber sheaths. The signals generated by the seismic detectors were sent to a modulation unit including an amplifying board and then recorded on magnetic tape by means of an analogical recorder with low power consumption and 160 h of tape duration. For power supply two 12 V batteries linked to four photo-voltaic modules for recharging were used.

THE RECORDED DATA

Debris flows in the Moscardo Torrent usually occur during the summer season, so the seismic network was installed at the end of spring and kept working until the beginning of autumn, both in 1995 and 1996. In 1995 a debris flow occurred in the Moscardo Torrent that was only recorded by the seismic detectors (Arattano, in press), because the gauging stations were out of order. In 1996, on 22 June and 8 July, two debris flows occurred that were recorded both by the seismic network and by the ultrasonic gauging stations 1 km downstream.

The passage of the surge is clearly visible in all the recorded seismograms, as it was expected, because of the vibrations produced by the presence of large boulders in the flow. However a significant record only began when the debris flows reached the location where each pair of sensors was placed. This is evidently due to a strong attenuation with distance of the vibrations produced by the debris flow itself. The propagation velocity of compressional P-waves in rocks like those present in the Moscardo basin ranges between 700 and 6000 m s^{-1} (Telford *et al.*, 1976). However the detectors are placed over a thick layer of alluvium and for this type of rock the wave velocity may be much lower. Seismic surveys carried out in the zone where the Moscardo Torrent is located have revealed velocities of P-waves in this alluvium as low as 350 m s^{-1} (Manfredini, 1977). The ratio of S-wave to P-wave velocity depends on the Poisson ratio; a value of 0.45 (for soft, poorly consolidated materials) would give S-wave velocity greater than 100 m s^{-1} (Arattano, in press). Even with such low velocity values, without a strong attenuation occurring along the 100 m long reaches between the sensors, the recording of the vibrations would have started almost simultaneously at the four sensors. The observed time interval between the inception of the recordings at the sensors is instead several seconds. This time interval is consistent with the time required for the debris flows to travel the distance between the sensors and is taken as the interval of time between the occurrence of the signal peak at the different sites.

The seismic recordings also reveal that the vibrations, in spite of the attenuation undergone along the reaches between the sensors, were strong enough to travel the distance of about 20 m between the torrent and the road that flanks it, where the sensors were placed (Fig. 2). This circumstance did not occur for a similar experience conducted few years ago to study bed load transport in an another mountain torrent (Govi *et al*, 1993). The vibrations induced by bed load transport were not intense enough to travel the distance of a few metres between the torrent bed and the banks. Only a detector buried directly under the torrent bed recorded the induced ground vibrations.

ANALYSES AND INTERPRETATION OF THE RECORDINGS

To process the recorded data the modulated signals, stored on magnetic tape, were demodulated and then converted to digital form with a precision of 16 bits and a sample frequency of 100 Hz s^{-1}. The data resulting from this conversion can be conveniently processed to obtain a more useful representation of the phenomenon. The digital recordings were in fact used to determine the arithmetic mean of the absolute values of ground oscillation velocity second by second (amplitude level). The output signals of the seismic sensors are voltages proportional to the ground oscillation velocity. In order to obtain the amplitude, they were converted to velocity values through the instrumental constant of transduction and the amplification value, and then the amplitude level was calculated as (Basile *et al.*, 1996):

$$A = \frac{\sum_{i=1}^{100} |v_i|}{100} \qquad (1)$$

where A is the amplitude, v_i is the ground oscillation velocity measured by the sensor and 100 is the number of digital samples present in each second of recording.

The amplitudes calculated using the data obtained through the two types of seismic sensors (type 1 and 2) for the 22 June debris flow are shown in Fig. 3 as a function of time. There is no significant difference between the results given by the two types of device: the same wave form has been recorded at the four sites by both of them. The oscillation velocities measured by the type 1 seismic sensors are generally greater, due to the different range of frequency in which the sensors work and to the fact that the seismometer is more sensitive than the geophone.

A different intensity of signal, after the passage of the main peak of the wave, can be observed for both types of sensor at the different sites. This difference in intensity is due to the position of the four pairs of sensors and to their different distances from the

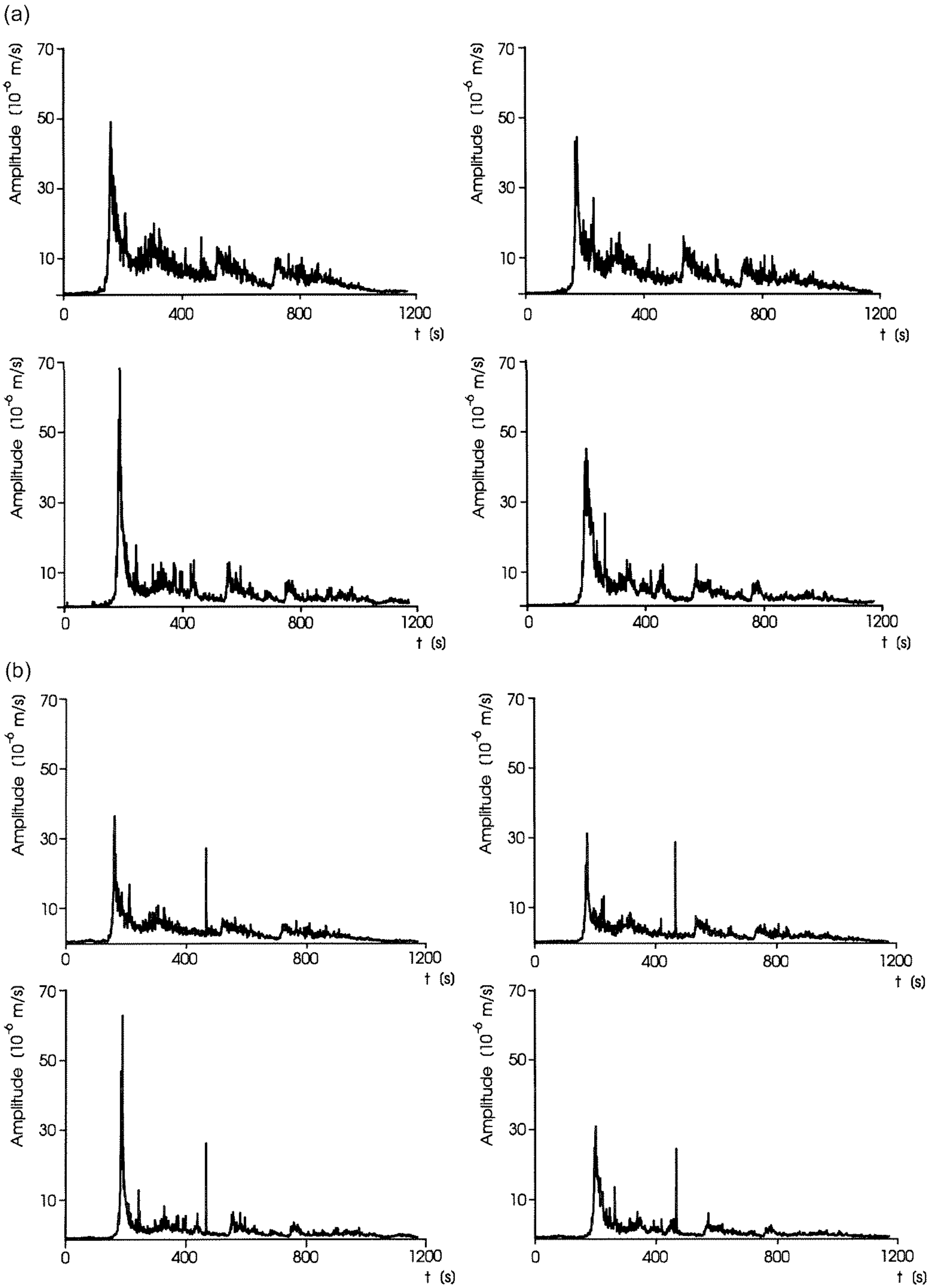

Fig. 3 Plot of mean ground vibration velocity *vs* time for the 22 June 1996 debris flow, measured through (a) seismometers (type 1 sensor); and (b) geophones (type 2 sensor). The origin of the time axis is arbitrary.

torrent bed (Fig. 2). The first pair of sensors is placed close to the check dam and the recordings show traces of the debris flow pouring over the check dam (a 5 m drop). The second pair of sensors is closer to the torrent bed than the others (at about 10 m distance) and this explains its more intense signal.

The graphs of Fig. 3(b) show, at about 470 s from the origin, a sudden and simultaneous increase of the oscillation velocity, which rises to 30×10^{-6} m s^{-1} and is attributed to an electrical disturbance. A smaller but simultaneous increase of the oscillation velocity due to the same reason can be also observed at the first site in the graphs of Fig. 3(a).

The passage of the debris flow front at the four stations is clearly identifiable in all graphs. These graphs have the form of waves that are recognizably similar to the debris flow waves commonly described by eye-witnesses or observed through ultrasonic recordings, both in the Moscardo and in other torrents (Pierson, 1985, 1986; Pierson *et al.*, 1990; Arattano *et al.*, 1997). In fact debris flows are generally described to move downvalley in a series of waves or surges with steep fronts that are usually higher than trailing portions (Costa, 1984). Another typical feature of a debris flow is the presence of superimposed, smaller waves travelling at velocities higher than those of the debris flow itself (Johnson & Rodine, 1984). This latter feature, in particular, is clearly present in the graphs of Fig. 3, in which three small waves can be identified behind the main surge, and is further confirmed by the velocity measurements that have been performed and that will be presented in the following. The smaller waves that follow the main front move more or less at the same velocity as this latter at the seismic site and are much faster than the front at the gauging stations, that is when the debris flow has reached the fan.

In Fig. 4, the hydrograph recorded by the upstream ultrasonic sensor (sensor A, Fig. 1) on 22 June 1996 is shown for comparison. The graphs of Fig. 3 and the hydrograph of Fig. 4 closely resemble each other, showing identical features easily recognizable on both of them. A main surge with a sharp peak is clearly visible on all graphs. The three smaller peaks that follow the main one on the amplitude *vs* time graphs can be identified easily on the hydrograph too. This indicates that the average velocity of ground vibrations is quite certainly a function of flow depth.

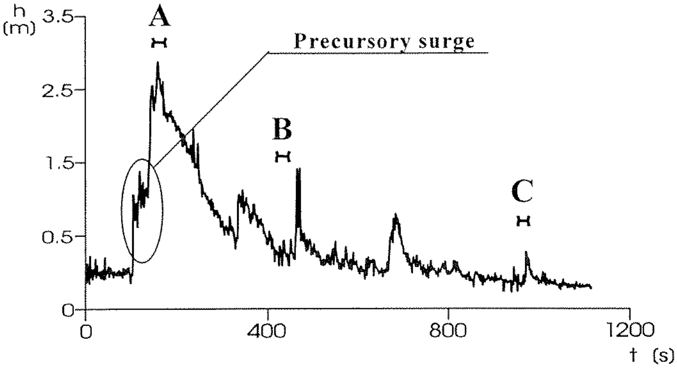

Fig. 4 Hydrograph of the 22 June 1996 debris flow recorded by the upstream ultrasonic sensor (labelled A in Fig. 1). The origin of the time axis is arbitrary. A, B and C indicate where the power spectra of Fig. 7 were determined.

However the front portion of the surge on the graphs of amplitude *vs* time is narrower than on the hydrographs, that is the ground vibration velocity measured by the seismometers decreases faster behind the main peak than the flow height measured by the ultrasonic gauges behind the main front. Moreover, the waves that have followed the main peak are smaller in Fig. 3 than on the hydrograph of Fig. 4. These two facts might indicate a dependency of the amplitude on grain size also. In fact the available video images of the event, recorded through a video camera placed nearby the ultrasonic sensor B in Fig. 1 (Arattano *et al.*, 1996), show the presence of very large boulders in the front of the flow and a rapid decrease in the number of these boulders after the front has passed by. The smaller waves that follow the main surge appear instead to consist mainly of mud with much fewer boulders than the main front. This might explain both the fast decrease in the ground vibration velocity behind the main peak and the smaller dimension of the tracks produced by these waves in the seismic recordings.

The video images of the event also show the presence of a hyperconcentrated surge that preceded the main peak of the debris flow (Arattano *et al.*, 1996; Arattano & Marchi, 1998). The ultrasonic sensors recorded this precursory surge, clearly visible in the hydrograph of Fig. 4. The passage of this part of the flow was not evident in the seismographs: the graphs of Fig. 3 present an abrupt rise of the vibration velocity that directly reaches its peak value. This difference might be explained both supposing that the precursory surge was not present at the seismic site or because this surge was not capable of producing enough ground vibrations. The installation of a seismic detector in the vicinity of the ultrasonic gauges might help to answer this question and might also provide a calibration useful for further uses of seismic detectors as monitoring and warning systems for debris flows (Arattano, in press).

The presence of the sharp increase of the vibration velocity at the passage of the main front, visible in Fig. 3, has allowed an estimation of the mean velocity of this latter along the torrent reach where the seismic network was placed. The mean velocity is determined by calculating the ratios of the distances between the sensors and the time intervals between the occurrence of the amplitude peaks at the sensor sites. The results are shown in Table 1.

The main front has also produced sharp peaks in all the hydrographs recorded at the ultrasonic gauging stations, as can be observed in the hydrograph of Fig. 4. This has allowed measurement of the mean front velocity at the gauging sites, similar to that at the seismic stations: the velocities have been calculated as the ratios of the distances

Table 1 Mean front velocities of the main surge and of some following waves at the seismic and ultrasonic gauging sites.

	Between seismic sensors 1 and 2 (m s^{-1})	Between seismic sensors 2 and 3 (m s^{-1})	Between seismic sensors 3 and 4 (m s^{-1})	At the ultrasonic gauging site (m s^{-1})
Mean front velocity of the main surge	7.1	8.5	7.2	3.5
Mean front velocity of the second of the following waves	7.1	7.1	7.7	7.5
Mean front velocity of the third of the following waves	6.7	6.7	7.1	7.1

between the ultrasonic devices and the time intervals between the occurrence of the peak height in the hydrographs. The results of such calculations are shown in Table 1 for comparison.

The mean channel slope at the gauging stations is about 10.4%, while at the seismic site it is 14.9%. A decrease of about one third of the slope results in halving of the mean front velocity. The mean velocities of the second and third wave that followed the main front have also been calculated and are shown in Table 1 together with the corresponding values measured at the gauging stations. These subsequent waves maintained the same velocity between the two sites and in fact they appear closer to the main front at the gauging station. It has not been possible to calculate the velocity of the first of the subsequent waves at the seismic site due to the difficulty in isolating clearly its peak and time of arrival.

The results obtained for the debris flow of 22 June 1996 have allowed an interpretation of those obtained for the debris flow of 8 July 1996 (Fig. 5). In this latter case, the graphs of amplitude *vs* time do not allow the identification of a single front and their shape is not immediately comparable with that of the corresponding hydrograph recorded at the gauging station (Fig. 6). However, assuming a proportionality between amplitude and flow depth, the existence of which has been revealed by the recordings of the first debris flow, the graphs of Fig. 6 can be interpreted as the result of the concurrence at the seismic site of several debris flow waves of similar magnitudes (at least four seem to be recognizable in the graphs) that have evolved in the single wave subsequently recorded by the ultrasonic sensors. This latter wave shows tracks of the presence of the four waves recorded at the seismic site.

Debris flows may originate at different locations along the torrent and thus may require different times and distances before a wave form is developed that is able to maintain the same aspect during its propagation down the channel, as appears to have

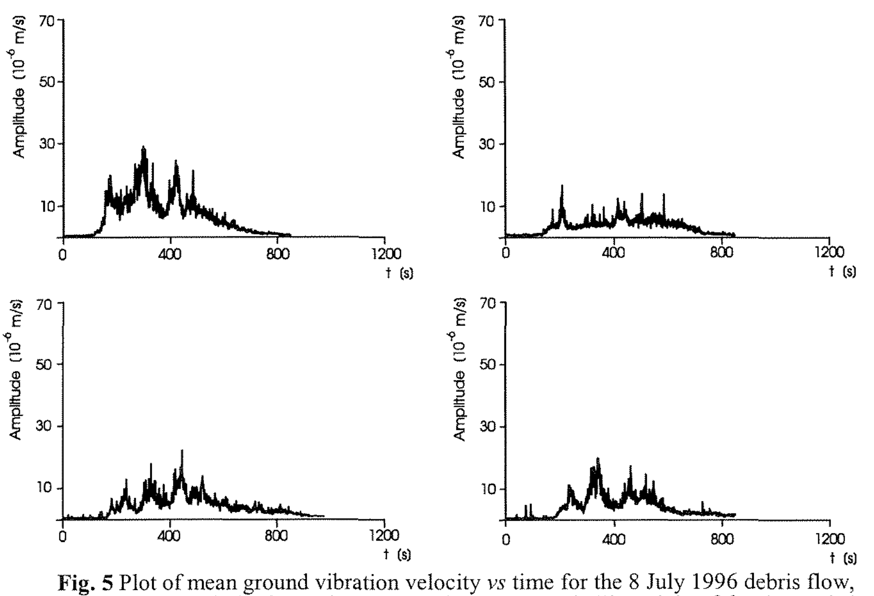

Fig. 5 Plot of mean ground vibration velocity *vs* time for the 8 July 1996 debris flow, measured through the four seismometers (type 1 sensor). The origin of the time axis is arbitrary.

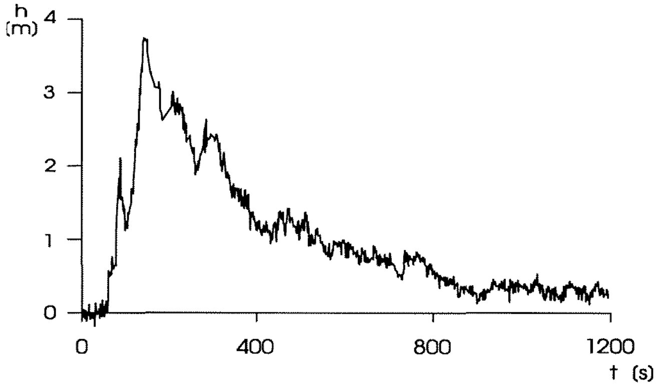

Fig. 6 Hydrograph of the 8 July 1996 debris flow recorded by the upstream ultrasonic sensor (labelled A in Fig. 1). The origin of the time axis is arbitrary.

happened for the June event. The July debris flow has probably collected further material between the seismic and the gauging sites, increasing its volume, particularly of its frontal part. In fact the amplitude graphs appear less intense for this second debris flow than for the first, but the 8 July hydrograph at the gauging site was much greater than that for 22 June. Further material between the two sites might have been provided both by shallow landslides on the slopes along the torrent and by erosion produced by the passage of the debris flow in the torrent bed. Further seismic sensors along the channel might help in identifying these occurrences.

The power spectra at different stage of the event (see Fig. 4) have also been analysed for the 22 June debris flow. The disturbance produced by the passage of the debris flow wave has a frequency component that ranges between 2 and 27 Hz in the peak region, in the middle of the wave and in the tail (Fig. 7). A significant frequency range can be found around 14–17 Hz. This frequency range is similar to that induced by bed load transport, which has been found to be clearly distinguishable from the frequency range of clear water (Basile *et al.*, 1996). The amplitude of power spectra is different in the three examined stages of the event. In fact there is an amplitude factor greater than 100 between the power spectra calculated in the tail region and those calculated in the middle of the wave, and a factor greater than 10 between the middle and the peak regions. These experimental results regarding frequency ranges might help in identifying and differentiating debris flows from water floods through the use of seismic devices.

CONCLUSIONS

A set of seismic sensors placed on the bank of a straight reach of a debris flow prone torrent has recorded the ground vibrations induced by the passage of two debris flows in the summer of 1996. These records provide some information about the detected debris flows, particularly if compared with the ultrasonic records that are available for the same events.

The field experiments in the Moscardo Torrent have shown that a significant

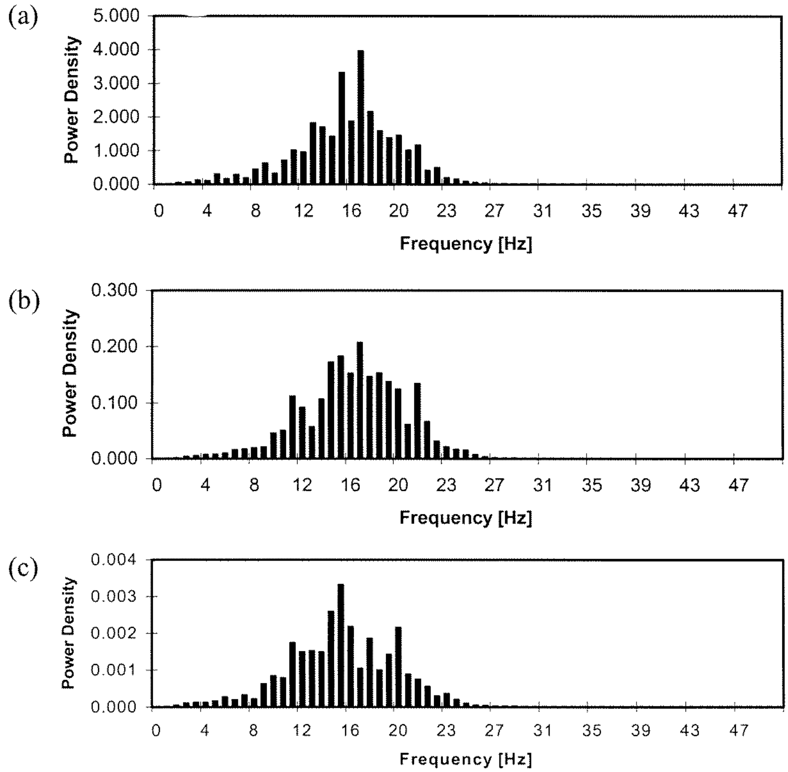

Fig. 7 Power spectra determined (a) in the peak region, (b) in the middle and (c) in the tail of the wave for the 22 June 1996 debris flow (see Fig. 4 for the corresponding positions on the hydrograph at which the power spectra were determined).

recording of the ground vibrations induced by a debris flow only starts when this latter arrives close to the site where the seismic sensor is placed, due to a strong attenuation of these vibrations with distance from the source (the debris flow itself). The propagation velocity of elastic vibrations in rocks such as those present in the examined basin is certainly greater than 100 m s^{-1}. Such a velocity would have required fractions of second for the vibrations to travel the distance between the sensors. Instead, the time interval between the inception of the recordings, or the occurrence of the peak at different sensors, is several seconds and is consistent with the time required for the debris flow to travel the longitudinal distance between the locations of the sensors. However the vibrations, in spite of their attenuation, have been demonstrated to be strong enough to travel the transverse distance (of several metres) between the torrent bed and the sensors placed on the banks.

The fact that the recording only started when the debris flow got close to the detectors has allowed an estimation of the mean velocity of the main front for the first of the recorded events. Plots of mean velocity of ground vibration *vs* time have allowed clear identification of the passage of the main front at the four stations. The mean velocity of this front was 7.6 m s^{-1}. Three smaller surges followed the main one: the mean velocities of the second and third of these surges were 7.3 and 6.8 m s^{-1}, respectively.

As previously mentioned, it was also possible to compare the graphs so obtained with the hydrograph recorded at a gauging station 1 km downstream of the seismic site. The two types of graph closely resemble each other, showing features recognizable in both of them. Ground oscillations appear to be a function of flow depth and grain size. A decrease in the mean velocity of the main front has been observed between the two sites, while the velocity of the front of the following waves remained more or less the same.

The results obtained for the first debris flow have allowed an interpretation of those obtained for the second. In this latter case, in fact, the amplitude *vs* time graphs do not allow the identification of a single front and their shape is not immediately comparable with that of the corresponding hydrograph recorded at the gauging station. However the proportionality between amplitude and flow depth revealed by the first debris flow has allowed some interpretation of these results.

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