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On the Use of Seismic Detectors as Monitoring and Warning Systems for Debris Flows

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Abstract. Debris flows constitute a major threat for several urban settlements located on the fans of mountain catchments and for other infrastructures that interact with these fans, particularly highways and motorways. Often structural measures such as the construction and maintenance of deposition basins, check dams, channel linings are both too expensive and not capable of completely guaranteeing the safety for inhabitants of villages and users of infrastructures affected by debris flows. Therefore the search of functional, reliable and possibly not expensive warning systems should be pursued to increase the available tools to face this often devastating kind of phenomenon. In this paper the use of seismic detectors for the determination of a debris flow occurrence in a torrent before its arrival on the fan will be discussed, together with their potential use as monitoring and warning systems. In 1995 a set of four seismic detectors was placed at a distance of about one hundred meters from each other along a straight channel reach of a debris flow prone torrent located on the Eastern Italian Alps. The purpose, in a first phase of the research, was mainly to verify which information could be obtained through this type of device on the occasion of a debris flow occurrence. On 5 July 1995, 22 June and 8 July 1996 three debris flows were recorded by this seismic network: the data that have been collected will be presented and conveniently processed for their interpretation. The results that have been obtained show that the passage of a debris flow in a torrent can be clearly identified using seismic devices placed at a safe distance from the channel bed and that in some cases a velocity estimation of the flowing mass is also possible through the processing of the seismic data.

Key words: debris flow, monitoring and warning systems, seismic detectors, hazard mitigation.

1. Introduction

Different types of ground vibration detectors (accelerometers, velocimeters, geophones, groundophones) have already been used by several researchers around the world to monitor debris flows, snow avalanches and bed load transport (Suwa and Okuda, 1985; Banziger and Burch, 1990; Zhang, 1993; Govi *et al.*, 1993, Decker *et al.*, 1997; Itakura *et al.*, 1997). However few field data have been collected so far on the vibrations induced by these natural phenomena and on the best methods to record them. This is particularly true with regard to debris flows.

More studies and field investigations on this subject might lead to the exploitation of the ground vibrations induced by debris flows to better deal with this hazardous phenomenon. This might happen through the development of warning tools and procedures as those already proposed by Decker *et al.* (1997) for the mitigation of the hazard caused by snow avalanches to the road networks in Utah and that is being tested in that State. At this moment similar procedures are not yet available nor satisfactorily tested for debris flows. Structural measures for debris flows hazard mitigation are often not capable of completely guaranteeing the safety for those who might be affected by this often devastating kind of phenomenon, therefore the purpose of mitigating debris flow disasters should be pursued not only modifying the natural system behaviour but also trying to modify the human behaviour (Davies, 1997). Within this contest, the development of functional and reliable warning systems might be of some help.

Following this idea in the Summer of 1995 a seismic network was installed in a debris flow prone catchment on the Eastern Italian Alps (the Moscardo catchment) that was already known to produce at least one debris flow per year (Arattano *et al.*, 1997). Between 1989 and 1994 twelve debris flows had in fact been recorded in this torrent by two gaging stations placed on its fan and peak flow depth larger than 2 meters had been measured for several of these events. The Moscardo Torrent debris flows had been also found to move and carry boulders of several cubic meters in volume as those shown in Figure 1. These debris flows were therefore considered to be able to produce ground vibrations strong enough to be recorded by seismic detectors placed on the banks of the torrent.

2. Location of the Seismic Detectors within the Basin and their Disposition Along the Monitored Reach

A debris flow is a moving source of ground vibrations, consequently two velocities are involved in the process: the velocity of the moving mixture of water and debris itself and the propagation velocity of the vibrations (waves) that it induces in the ground (Figure 2). This must be taken into account as far as monitoring activities through seismic detectors are concerned and the values of these two velocities, in the particular basin chosen for the investigations, have to be previously estimated for a convenient disposition of the detectors along the torrent.

One type of wave that a debris flow, as any other ground vibration source, can generate in the ground is the compressional or P-wave. The propagation velocity of compressional waves in rocks like those present in the Moscardo basin, that is slate, shale, sandstone, limestone and breccia (Arattano *et al.*, 1997), ranges between 700 and 6000 m/s (Telford *et al.*, 1976). These velocities are certainly much higher than those reachable by a debris flow wave propagating along a natural channel. However the banks of the Moscardo torrent, where the detectors are placed, mainly consist of alluvium and in this type of rock P-wave velocity may be much lower. The lowest possible value of this latter velocity must be known, at least its order of magnitude, to verify whether it is comparable or not with the propagation velocity of a debris flow wave. This latter occurrence might in fact impede a distinction, in the interpretation of the recordings, between these two velocities and the related phenomena.

Figure 1. The Moscardo Torrent debris flows can carry boulders of several cubic meters in volume. These two large boulders were deposited along the reach of the torrent that crosses the fan by a debris flow occurred in the summer of 1996.

Some data on the propagation velocity of seismic waves in the type of alluvium present in the zone where the Moscardo torrent is located were already available. Seismic surveys had in fact been carried out in this latter zone after the earthquake that hit the Friuli Venezia Giulia region in 1976. These surveys showed that the lowest velocity of P-waves in this alluvium is of 350 m/s (Manfredini, 1977).

Another type of wave that can be produced by the passage of a debris flow in a torrent and detected by a seismometer is the transversal or S-wave. S-waves velocity, β, is a fraction of the velocity of P-waves, α, that depends on the Poisson's ratio, σ, according to the following relationship (Telford *et al.*, 1976):

$$\frac{\beta}{\alpha} = \sqrt{\frac{\frac{1}{2} - \sigma}{1 - \sigma}}. \tag{1}$$

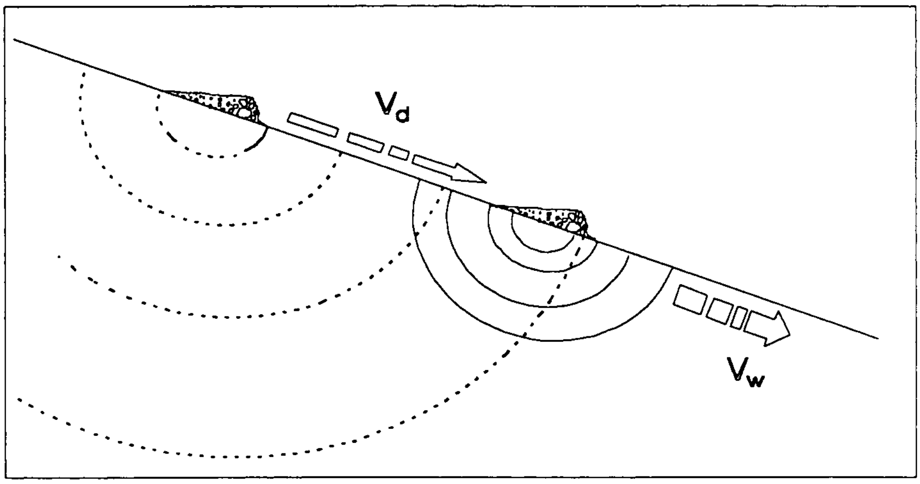

Figure 2. Two different velocities are involved in the propagation of a debris flow along a torrent: the velocity of the debris itself, V_d, and the propagation velocity of the vibrations that it induces in the ground, V_w.

Even assuming for the Poisson's ratio, σ, a value of 0.45 that holds for soft, poorly consolidated materials like those present in alluvium, β would result greater than 100 m/s (Telford *et al.*, 1976).

There are other types of waves, besides *S* and *P* waves, that might be involved in the process, however their velocities should still range between 100 and 350 m/s (Telford *et al.*, 1976).

As previously stated also the propagation velocity of debris flow waves has to be known for comparison. Some velocity data were already available that had been measured in the Moscardo Torrent between 1989 and 1994 (Arattano *et al.*, 1997) through ultrasonic gauges placed on the fan, where the channel slope is about 10% (Figure 3(a)). Mean front velocities of twelve debris flows occurred during that period ranged between 1 and 10 m/s. These values were comparable with those already observed by other authors elsewhere (Pierson 1985, 1986; Suwa, 1989; Pierson *et al.*, 1990; Takahashi, 1991). At the seismic site velocities might have been higher for larger events and they might have also been higher for the greater steepness of the channel at that position (about 15%). However mean flow velocity usually depends on the square root of channel slope (Pierson, 1986; Takahashi, 1991), thus only a difference of few meters per second at most could have occurred at the seismic site because of its greater steepness. A difference of one order of magnitude at least was therefore expected between the velocity of debris flows similar to those already observed and the propagation velocity of the ground vibrations induced by them.

On the basis of these considerations four seismic detectors were placed at a distance of 100 meters from each other along the right bank of a straight reach of the torrent located in the lower basin few hundred meters upstream of the fan apex

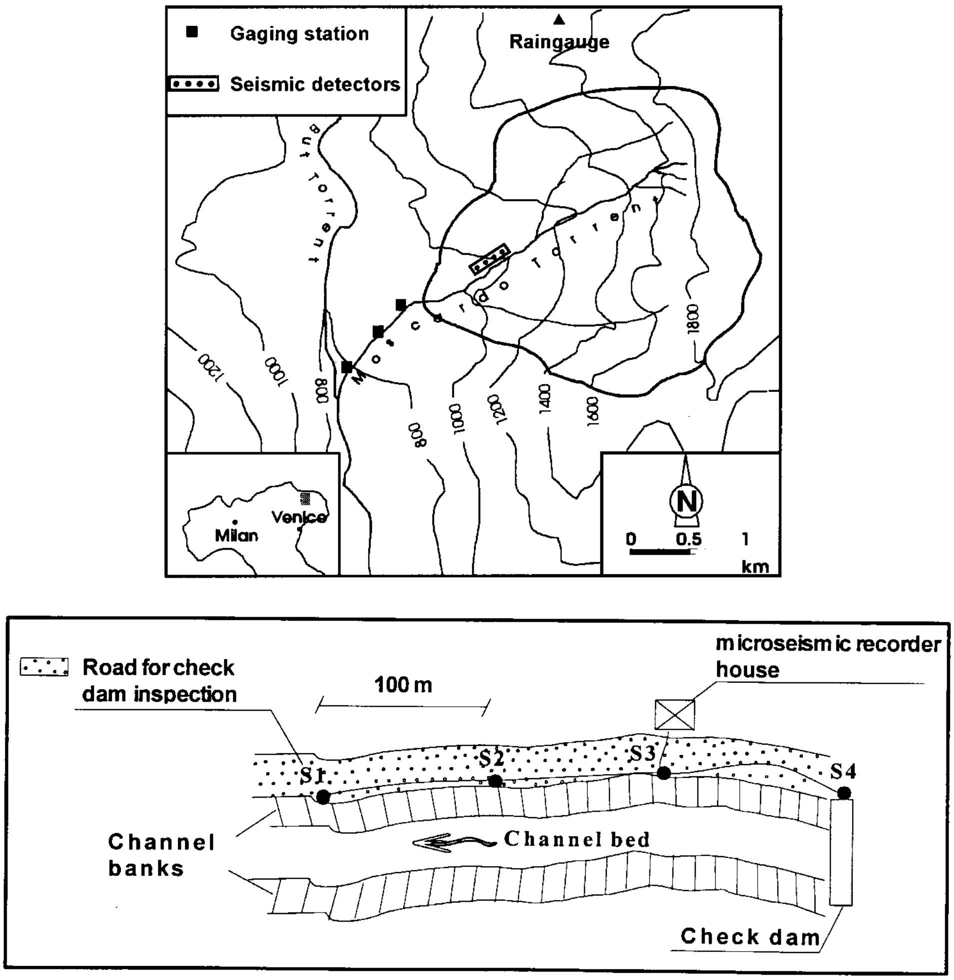

Figure 3. (a) Location of the seismic network within the Moscardo Basin closed at the fan apex. The lower basin was chosen for the installation to guarantee the possibility to record the point of movement inception, the safety of the installation and its accessibility. (b) The seismic detectors (S1, S2, S3 and S4) were placed at a distance of 100 meters from each other along the right bank of a straight reach of the torrent.

(Figure 3(a)). The distance between the detectors was chosen to guarantee a good approximation of the debris flow velocity estimations obtainable through the seismic signals. These estimations were thought possible identifying in the recordings one or more clearly recognizable features having constant time lags between their occurrence at consecutive sensors. Such features could have been ascribed to the passage of some peculiar portion of the debris flow, such as the main front or a secondary wave, in the vicinity of each sensor. A typical debris flow is in fact a large wave with a steep front, consisting mostly of large boulders, usually followed by superimposed, smaller waves having lower front heights (Johnson and Rodine,

1984) and debris flows showing such characteristics had been already observed in the Moscardo Torrent (Arattano *et al.*, 1997).

The presence of boulders in the main front of a debris flow and in its following surges was expected to generate particularly intense ground vibrations that could have been traced back in the seismographs as recognizable features of the recorded signal. The ratio of the distance between each couple of consecutive detectors to the time lag between the occurrence at those detectors of one of these particular features would have led to a velocity estimation for this latter and for the entire event. The value of this time lag would have had to be of several seconds, that is consistent with the time needed by the wave to travel the distance between two consecutive sensors. For a debris flow velocity as high as 10 m/s, a distance of 100 meters between each couple of sensors would have led to an average error of about 10% in its estimation.

Another reason that led to the choice of the distance between the sensors and their location within the basin (Figure 3(a)) was the attempt to record the moment of movement inception. Debris flows triggered in the upper basin by a landslide or by the collapse of a channel dam were in fact thought capable of producing ground vibrations strong enough to travel the distance between the point of their occurrence and the seismic network. A distance of one hundred meters between the sensors should have caused an almost simultaneous recording of such an occurrence at the four sensors, considering the propagation velocity of the ground vibrations previously estimated (> 100 m/s). This would have facilitated its recognition, impeding any confusion with recordings due to the passage of a debris flow wave[*] in the vicinity of the sensors. Moreover positioning the network in the lower basin (Figure 3(a)) was thought a good compromise among different needs: an eventual location on the fan, close to the gaging stations, might have been too far from the potential inception point: the eventual vibrations induced by the triggering of a debris flow might have dissipated before reaching it. On the other side no safe place was available in the upper basin because of its very steep and unstable nature.

An easy accessibility was also needed for the installation in order to be able to carry the equipment in place, to install it and subsequently perform inspections and management. The chosen location in the lower basin provided both these requirements. The presence of a road used by the Forest Service to inspect the check dam indicated in Figure 3(b) allowed in fact the accessibility, while the presence of a long, straight embankment that flanked the torrent provided a safe place for the installation of the four detectors.

3. Type of Detectors Used and Their Installation on the Ground

The seismic detectors that have been employed and the results of which will be presented in this paper are seismometers with a natural frequency of 1 Hz, placed

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[*] Or other disturbances, such as hyperconcentrated flows or small debris flow surges preceding the main debris flow event.

Figure 4. The detectors were placed on the ground in an upright position within a hole about 30 cm deep, subsequently refilled and compacted.

on the ground in an upright position within a hole about 30 cm deep, subsequently refilled and compacted (Figure 4).

These detectors have given the best response to the passage of the three debris flows occurred in 1995 and 1996; other types of detectors have also been tested (geophones with a natural frequency of 4.5 Hz) that have given weaker responses due to their smaller sensitivity. Since there was no mean to predict the occurrence of debris flows, the seismic signals were recorded continuously using an analogical magnetic tape recorder with very low power consumption and 160 hours of tape duration. Seismic signals might have been detected using a computer with a thresholds test to trigger the recording (Lepettre *et al.*, 1996), but the simpler

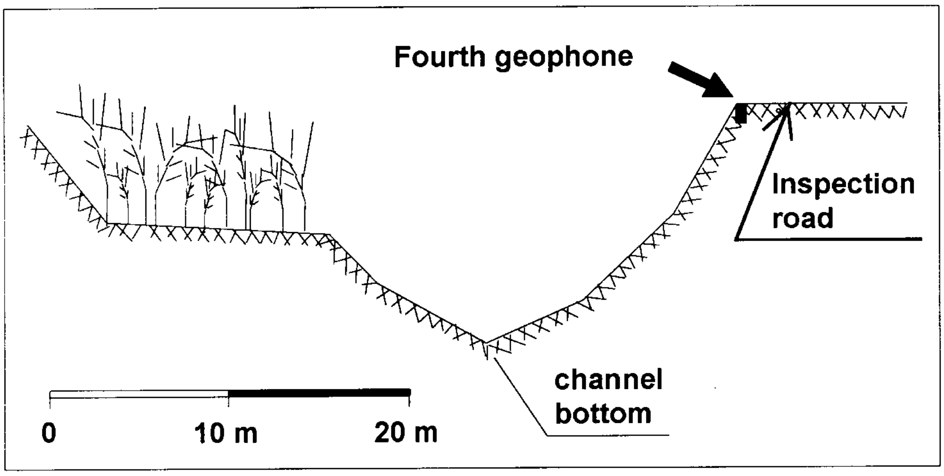

Figure 5. The sensors are placed on the border of the road that flanks the torrent at a distance of about 20 meters from the channel bottom. Here the cross section is shown where the fourth detector is installed.

solution provided by a continuous tape recorder was preferred in this first phase of research.

No information was available about the minimum distance from the torrent bed needed to guarantee a satisfactory recording of debris flows, except that in previous experiences regarding the monitoring of bed load transport only detectors directly placed in the stream bed had been found capable of recording ground vibrations (Govi *et al.*, 1993). The installation of the detectors directly in the torrent bed was not possible in this case for debris flows are known to produce often severe erosions and these erosions might have damaged, destroyed or even swept away the sensors. These latter were thus placed at a distance of about 20 meters from the torrent bed, on the border of the road that flanked it, that is in the closest available position that could still be considered safe enough (Figure 5).

Some tests might have been performed to verify the quality of the recordings, making some large boulder roll in the torrent to simulate a debris flow, but considering the difficulties involved in reaching the torrent with a bulldozer and, on the other side, knowing the high frequency of the events in the Moscardo Torrent (Arattano *et al.*, 1997), it was considered easier to install the network and wait for the occurrence of a debris flow.

4. The Recorded Events

On 5 July 1995, 22 June and 8 July 1996 three debris flows occurred in the Moscardo Torrent that were recorded by the previously described seismic network.

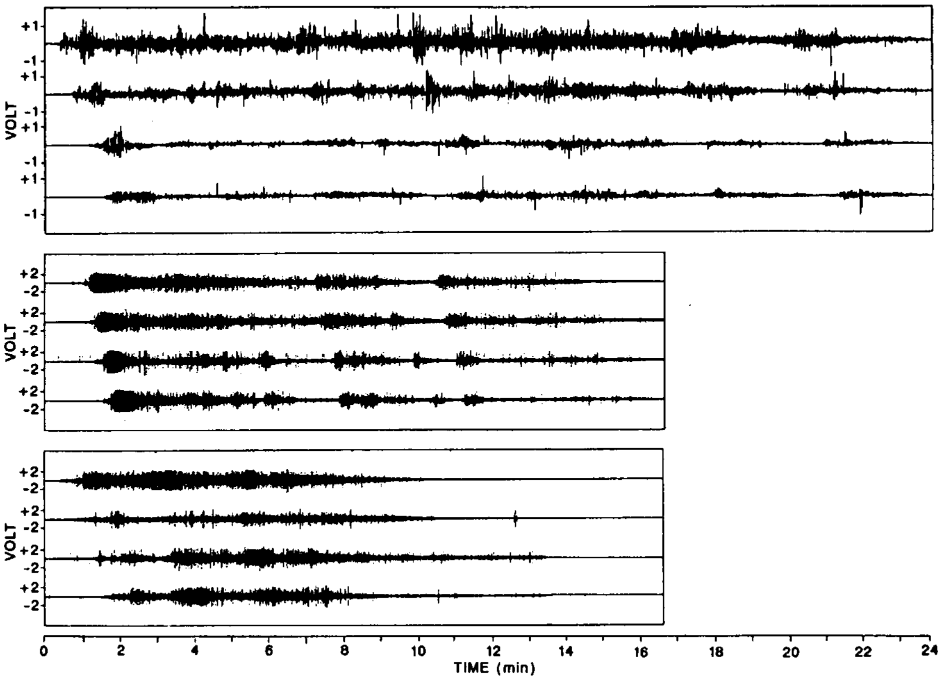

Figure 6. Output of the seismic detectors for three debris flows occurred in the Moscardo Torrent on 5 July 1995, 22 June and 8 July 1996 respectively.

In Figure 6 the output obtained by the recording system is plotted with the voltage as the ordinate and the time as the abscissa. The voltages can be easily converted in ground vibration velocity data, v_i, through an instrumental constant.

As it can be noticed, the passage of the debris flow wave is clearly visible in all three cases, its signal being way above the level of natural noise. The signal is generally more intense at the first sensor for it is close to the check dam previously mentioned and visible in Figure 3(b): the jump from this check dam evidently generates more intense vibrations. The recording seems to have only started when the debris flow reached the location of each sensor: in fact the time lag between the inception of the recording at two consecutive detectors is of several seconds, that is consistent with the time needed by the moving mixture to travel the distance between them. However the precise value of this time lag cannot be easily identified from the plots of Figure 6. The events had different duration that can be easily established from the recordings: about 27 minutes for the 1995 event, 18 minutes for the June 1996 event and 15 minutes for the July 1996 event.

All the recorded signals present a peak of intensity, few tens of seconds after the inception of the recordings. This peak can be ascribed to the passage of the debris flow front, a feature of debris flows that has been mentioned earlier. As it happened for the moment of recording inception, the exact time of occurrence of this peak cannot be easily identified. Further peaks appear in the seismographs behind the first peak, probably due to the presence of subsequent surges, another characteristic feature of debris flows observed in several circumstances (Johnson and Rodine, 1984; Suwa, 1989; Arattano *et al.*, 1997). However it is not always easy to pick out the presence of these surges in the three recorded seismographs. A debris flow surge should produce a peak followed by a regular decrease of ground vibration behind it. Three of such surges are clearly observable for the 22 June 1996 event, but the presence of them is less evident in the 8 July 1996 seismograph and almost absent in the 5 July 1995 one. As we will see again later, this is probably due to the fact that debris flows need to travel a certain distance from the inception point before clearly identifiable wave forms can develop. Nothing is known yet about the possible location of the inception points of the Moscardo Torrent debris flows. It is possible that some debris flows originate in the lower basin, close to the area where the seismic detectors are placed. If this were the case, at the seismic site some of the recorded debris flows might still have been collecting material eroded from the bed or provided by the slopes and thus have not yet developed neat wave forms. However this hypothesis needs further studies and data collection to be verified.

In Figure 7(a) one second of recording, taken from one of the plots of Figure 6, has been enlarged. The frequency of the vibrations can be easily determined from Figure 7(a). This signal can be converted in digital form sampling one hundred of voltage values each second, as shown in Figure 7(b): this allows a detailed enough description of the vibrations undergone by the ground in that interval of time.

The data resulting from the conversion in digital form can be conveniently processed to obtain a more useful representation of the phenomenon. In fact the arithmetic mean of the absolute values of ground oscillation velocity second by second can be determined (amplitude level) with the following expression (Basile *et al.*, 1996):

$$A = \frac{\sum_{i=1}^{100} |v_i|}{100}, \tag{2}$$

where A is the amplitude and v_i is the ground oscillation velocity that has been obtained multiplying the voltage values, sampled as previously described, by an instrumental transduction constant. The results of this data processing are shown in Figure 8 for the three recorded debris flows. For the 1995 event the processing has been possible only for the last three detectors, for the presence of several disturbances in the recording of the first seismic sensor.

The advantage of processing data in this way is that the presence of peaks and other features in the recordings becomes more visible and they can be more easily isolated and then recognized in the different seismographs. This is particularly true for the 22 June 1996 debris flow, for instance.

We mentioned in a previous chapter the possibility of performing debris flow velocity estimations through the seismic signals, identifying in the recordings a

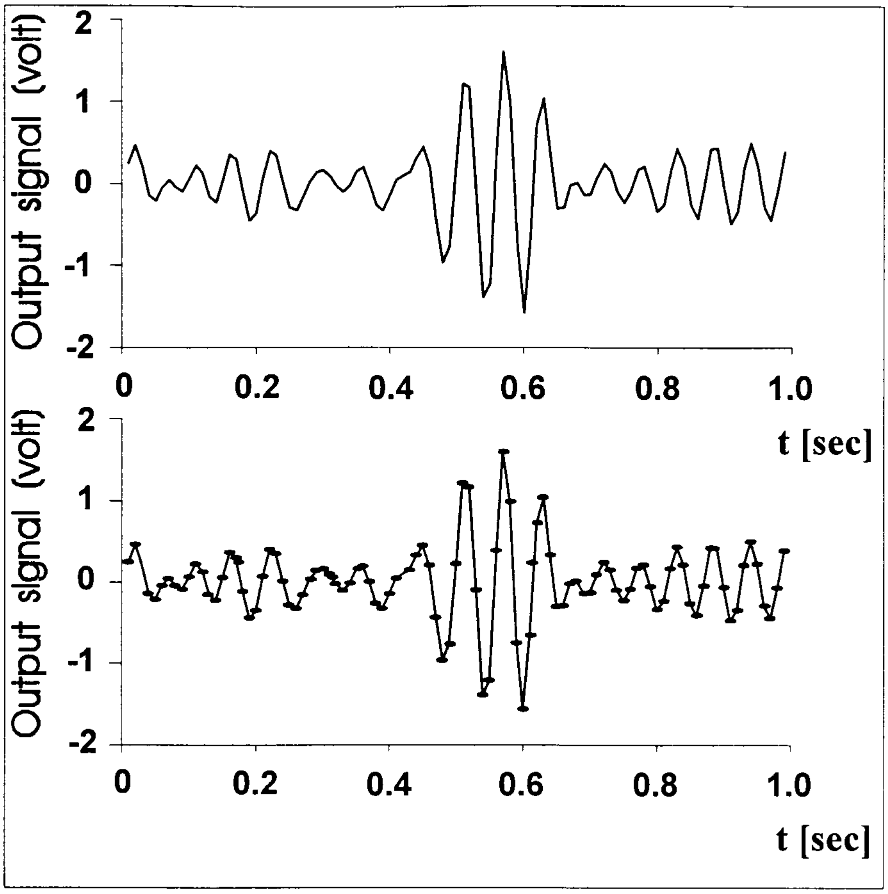

Figure 7. (a) Enlargement of one second of seismic recording of a debris flow passage; (b) this signal can be converted in digital form sampling one hundred of voltage values each second.

clearly recognizable feature having constant time lags between its occurrence at consecutive sensors. Such a feature is present in the recordings of the June 1996 event: a sharp peak, which can be assumed to be due to the passage of the main front of the debris flow wave, is in fact found in all the four graphs of Figure 8. Actually in the second and third graph two peaks are present that are very close to each other: in this case the highest of these two peaks has been assumed to correspond to the passage of the main front of the event. In fact the time lags between the occurrence of the highest peak at consecutive sensors are similar (14, 12 and 14 seconds respectively). On the basis of these values a mean front velocity of 7.5 m/s has been estimated for this event at the seismic network site.

The passage, and consequently the presence, of a main front is less evident for the remaining events, even though several peaks can be identified in the signals. However a correspondence among these peaks in the four recordings is not easily

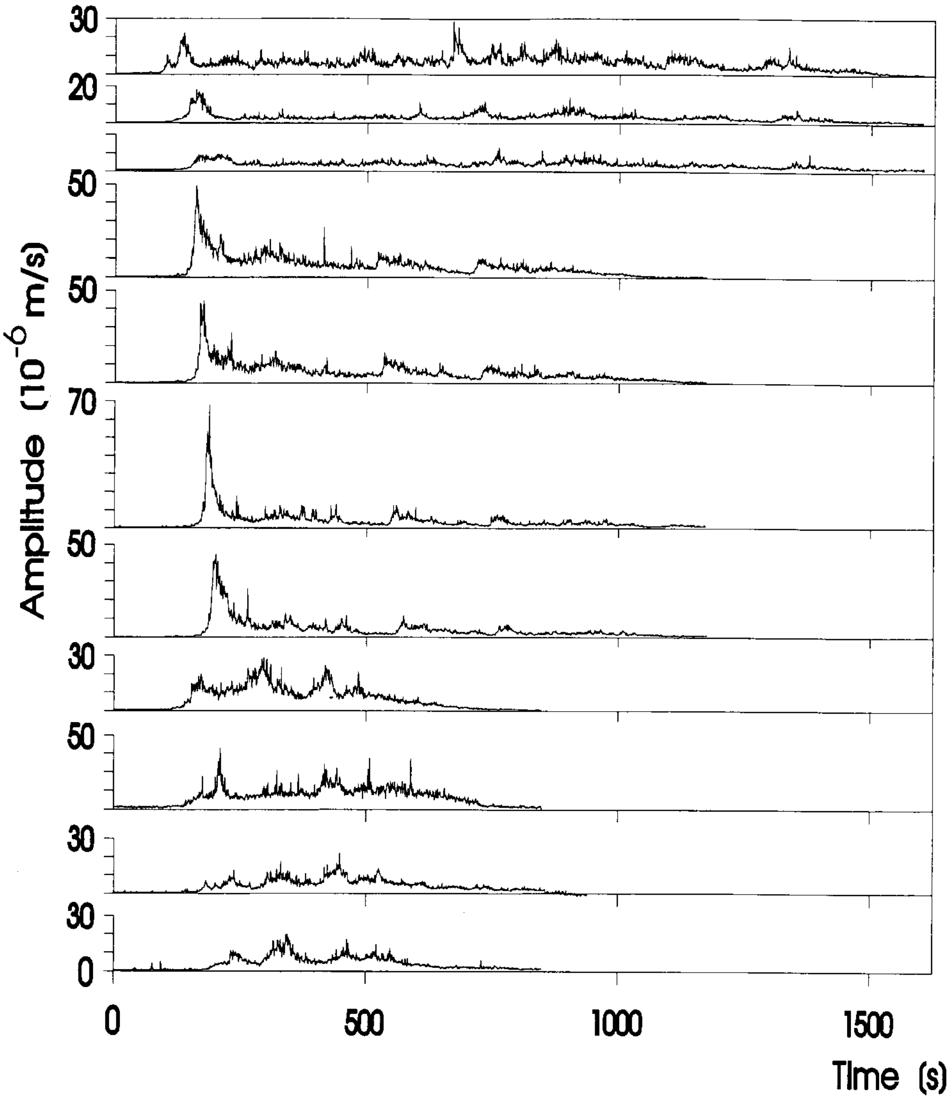

Figure 8. Plot of the amplitude versus time for the three recorded debris flows.

found. Therefore it has not been possible to easily perform velocity estimations in these cases. As mentioned earlier debris flows may originate at different locations along the torrent or keep collecting material eroded from the bed or provided by the slopes for different distances. As previously hypothesized they may need to travel different distances from their own inception points before a main front and a wave form can develop as those commonly observed for these flows on the fans (Johnson and Rodine, 1984; Pierson, 1986; Suwa, 1989; Arattano *et al.*, 1997). This might be a limitation if seismic sensors placed upstream of the fan are to be used for velocity estimations.

5. Applications of Seismic Detectors as Monitoring and Warning System

The research activity carried out so far in the Moscardo torrent was mainly intended to investigate the use of seismic detectors as monitoring devices for studying debris flows. The main goal, in a first phase of the research, was to verify which information could be obtained through this type of device on the occasion of a debris flow occurrence. The presence of characteristic features in debris flows, such as a steep front rich of large boulders or secondary surges behind this latter, was expected to produce analogous features in the seismic recordings allowing also velocity estimations. The development of methods for debris flow velocity estimations is particularly important since the existing tools developed and commonly used in hydraulics to measure flow velocities in natural channels, such as current meters, weirs, Venturi and Parshall flumes etc. cannot be safely utilised for debris flows, for the presence of large boulders and smaller fragments within the moving mass.

The possibility to perform velocity measurements locating in the seismic recordings features occurring with constant time lags at consecutive detectors, was actually verified for only one of the three debris flows recorded so far in the Moscardo Torrent. For the remaining events it was not immediate to locate such features in the seismographs probably because at the seismic site the corresponding debris flows had not yet entirely developed into a wave form with precise characteristics and have originated only at a short distance from the sensors. Actually little is known about the formation processes of debris flows and where they originate along the torrent: seismic detectors might reveal to be a tool for future investigations of this issue, particularly if more field data will be collected at different locations along the channel.

Even though the installations tested in the Moscardo Torrent were intended for research purposes, the results that have been obtained might encourage the use of seismic devices as warning system, as it is been doing for snow avalanches in Utah (Decker *et al*., 1997). Also debris flows often affect the road network producing high risk situations, as in the case of the Italian motorway cited by Arattano *et al.* (1991) that was already interested by debris flows in 1990 and was again damaged in 1996 by one of these events (Figure 9). Seismic detectors might be employed in this and similar cases as warning systems until structural and more definitive measures will be taken. More difficult would be the use of seismic detectors as warning systems for protecting villages, for debris flows are very fast phenomena that usually do not allow enough time for evacuation.

Seismic detectors present many advantages compared to other devices usually employed both for monitoring and warning purposes. Ultrasonic sensors, for instance, need to be hanged over the chanel through wires or more complex structures that are difficult to be installed where steep and unstable slopes are present along the torrent. Trip wires that are broken by the passage of the flow cannot detect subsequent flows without maintenance, are subject to breakage by animals or accident and are also difficult to install. Doppler speedometers (Suwa *et al*., 1993) are quite

Figure 9. Debris flows often affect highways and motorways producing high risk situations as in the case of this Italian motorway severely damaged by a debris flow occurred on June 1996 after an analogous event already occurred in 1990. Seismic detectors might be employed in this and similar cases as warning systems until structural and more definitive.

expensive and still require a clear visibility of the torrent bed and a structure to sustain them that needs a safe place for its installation. The same can be told of spatial-filter speedometers (Itakura *et al.*, 1985; Itakura and Suwa, 1989) and of video cameras (Inaba *et al.*, 1997). These latter may also have problems to monitor debris flows occurring at night. On the contrary, seismic sensors can be also placed quite far from the torrent bed, they need neither necessarily visibility of the torrent, nor structures to sustain them, nor have they any particular problem at night.

It must be noticed that the monitoring devices previously indicated have different purposes as far as monitoring is concerned. Ultrasonic sensors are devoted to record the variation of the stage during the occurrence of a debris flow, even though a couple of these sensors placed at a known distance along a torrent may also provide mean front velocity estimations. Trip wires can detect the maximum flow depth according to the highest broken wire and sets of such wires placed at different sites again can provide an estimation of mean front velocity. Doppler speedometers and spatial filter speedometers are employed for surface velocity measurements and also video cameras have been already employed for this scope (Inaba *et al.*, 1997). Seismic devices might actually reveal to be useful for different purposes, even though further studies and improvements would be required. A calibration of the seismic signal for instance, obtained placing a seismic detector close to an ultrasonic sensor to compare the results, might in fact allow the use of these detectors to monitor variations in stage. Moreover the processing of seismic data to emphasize features in the recordings might allow mean velocity measurements along the debris flow wave.

6. Conclusions

A set of four seismic detectors, placed at a distance of one hundred meters from each other along a debris flow prone torrent, has recorded the passage of three debris flows occurred in the summer of 1995 and 1996. The recordings show that the passage of a debris flow in a torrent can be clearly identified using seismic devices placed at a safe distance from the channel bed. Through a convenient processing of the recorded data, a velocity estimation of the flowing mass has also been possible in one case. The purpose of the installation, in this first phase of the research, was essentially to verify which information could be obtained through this type of device on the occasion of a debris flow occurrence, but the results obtained are quite encouraging for future applications of these detectors as monitoring tools for this type of mass movement. The investigations of the ground vibrations induced by debris flows presented in this paper might also provide some useful data for the development of warning procedures for debris flows hazard mitigation.

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