Original Article

Methods of Data Processing for Debris Flow Seismic Warning

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The output of the seismic devices commonly employed for the monitoring of debris flows, such as geophones and seismometers, is a voltage that is directly proportional to the ground vibration velocity. The output signal in analogical form is usually digitalized at a fixed sampling frequency to be opportunely processed. The processing is performed to both reduce the amount of data to be stored in a data-logger and to reveal the main features of the phenomenon that are not immediately detectable in the raw signal, such as its main front, eventual subsequent surges, the wave form and so on. The processing also allows a better and sounder development of algorithms, when seismic devices are employed for warning purposes. However, the processing of the raw signal alters in different ways the original raw data, depending on the processing method adopted. This may consequently limit or reduce the efficacy of the warning. Different methods of data processing can be found in literature, each with its own advantages and shortcomings. In this paper we will explore and discuss the effects of some of these latter on the efficacy of the algorithms employed for warning, applying them to the seismic recordings obtained in the instrumented basins of Gadria (Italy), Rebaixader (Spain) and Illgraben (Switzerland).

Key words: debris flow, seismic monitoring, geophone network, warning system

1. INTRODUCTION

Debris flows are one of the most hazardous mass movements that may occur in mountainous regions. In the Alpine region, they cause severe damage to settlements and infrastructure and several casualties every year [*Guzzetti et al.*, 2005; *Hilker et al.*, 2009]. Several debris flow prone basins have been instrumented in mountain ranges worldwide [*Berti et al.*, 2000; *Marchi et al.*, 2002; *Badoux et al.*, 2008; *Chou et al.*, 2010; *Navratil et al.*, 2013; *Coviello et al.*, 2015], with a variety of sensors in order to increase the knowledge on their occurrence and behavior. The data collected in these monitoring sites are not only needed for scientific purposes, such as the calibration of numerical models and the investigation of rheological behavior [*Iverson*, 1997; *Coussot et al.*, 1998; *Arattano et al.*, 2006], but also to develop and test warning systems.

The propagation, the fragmentation and the collision of the debris flow mixture with the channel bed, generate seismic waves in the ground. These vibrations can be measured by seismic and sonic devices such as geophones, seismographs or infrasound detectors [*Itakura et al.*, 2005; *Kogelnig et al.*, 2011]. There are several existing methods to collect and process the output data of the seismic sensors (ground vibration velocity). However, not much is known about the advantages and limitations of their use for early detection purposes.

In this work, data from three different instrumented debris flow torrents are analyzed (**Fig. 1**). Two different seismic data processing methods are compared: the Impulse method and the Amplitude method. The general purpose of this work is to improve the knowledge on the debris flow warning issued through seismic devices. The

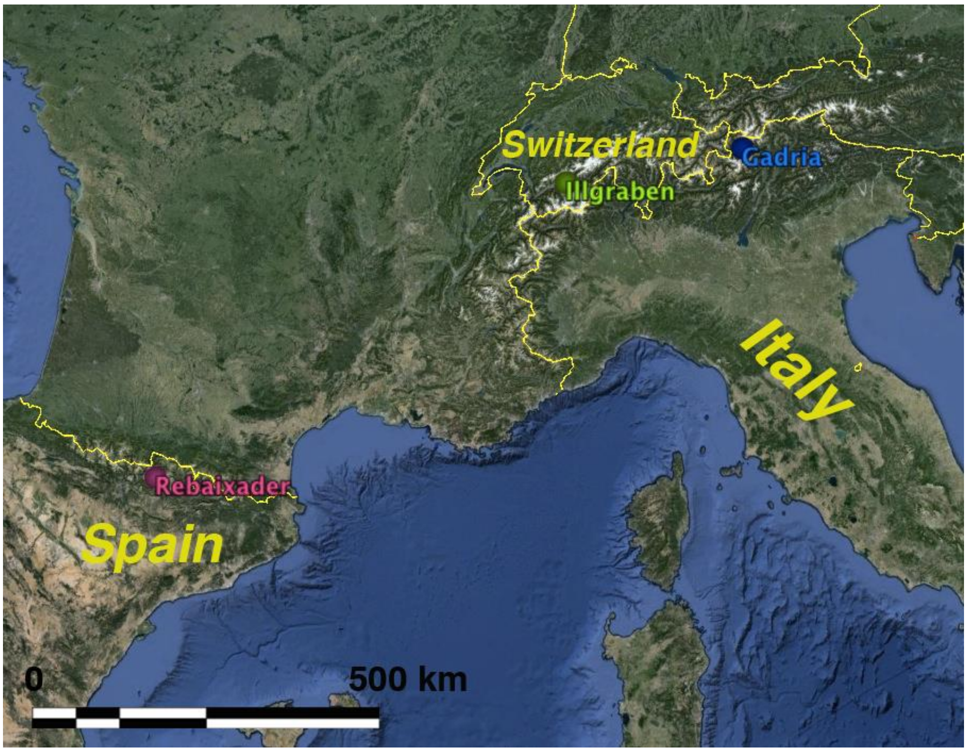

Fig. 1 Location of the three debris flow instrumented basins where data presented in this paper have been collected: the Rebaixader (Spanish Pyrennes), the Illgraben (Swiss Alps) and the Gadria (Italian Alps).

specific goal is twofold: (i) the comparison of two well-known seismic data processing methods: impulse and amplitude and (ii) the analysis of the effects of applying these two methods for the early detection of debris flows.

2. WARNING ALGORITHMS BASED ON SEISMIC SIGNALS

Seismic devices have already been proposed and employed as warning sensors [*Badoux et al.*, 2008; *Abancó et al.*, 2014]. However, scholarly studies on this specific issue are still scarce. The topic, in fact, would still need much effort to reach a standardization of the application procedures, as it occurs for many other aspect of the use of seismic devices for the monitoring of debris flows. Commonly, the detection of the occurrence of a debris flow through seismic devices requires first an analysis of the output signal through a specific algorithm. Warning algorithms, however, are usually applied after an initial processing of the signal. This can be carried out through different methods, each with its advantages and shortcomings [*Arattano et al.*, 2014].

The algorithms proposed or applied so far in literature usually require, for issuing an alarm, that a predefined threshold of the value of the processed signal is exceeded for more than a pre-established number of seconds [*Badoux et al.*, 2008; *Abancó et al.*, 2014]. Similar algorithms are also applied when stage sensors are used as warning devices: in this case the threshold is a predefined value of the stage.

Figure 2 clearly shows an important advantage that ground vibration detectors have, in comparison with stage sensors. **Fig. 2(b)** displays the hydrograph recorded by a radar sensor for a debris flow which occurred on July 18, 2014 in the Gadria torrent [*Comiti et al.*, 2014]. For comparison, the seismic signal processed with the amplitude method, recorded for the same event by a geophone installed at the same cross-section is also plotted (**Fig. 2(c)**). The figure clearly shows how the geophone can be used to detect the occurrence of the debris flow tens of seconds in advance. The amplitude, in fact, start to rise more than 20 seconds before the occurrence of the amplitude peak. On the contrary the stage starts its raise just few seconds before the stage peak. Notice that the geophone that has recorded the graph shown in **Fig. 2** is installed in the wing of a check dam. This produces a certain amount of damping of the signal. For geophones installed directly in the terrain the start of the raise of the signal may occur up to 50–60 seconds in advance [*Coviello et al.*, 2015]. These results are consistent with other observations made in the Illgraben basin, where a debris flow was detected with a broadband seismic sensor before it reached the in-channel location nearest the station, giving rise to a progressive increase of the seismic energy [*Burtin*

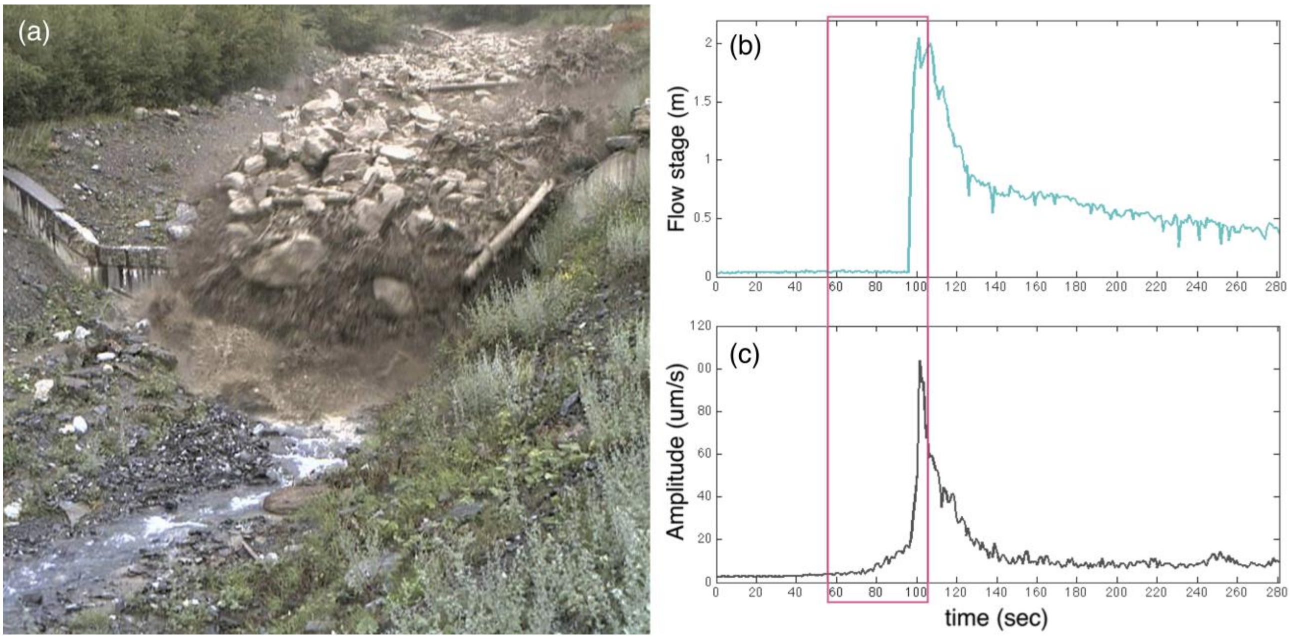

Fig. 2 Debris flow occurred in the Gadria basin (Lasa, Bz, Northeastern Italian Alps) on July 18, 2013; a) arrival of the main front, b) hydrograph and c) amplitude graph. In the amplitude graph the detection of the debris flow arrival occurs more than 20 seconds before the occurrence of the peak.

et al., 2014].

It clearly emerges from **Fig. 2** that developing and adopting an appropriate algorithm for the real time processing of seismic monitoring data can provide an additional few tens of seconds to the issue of the alarm, compared to the use of a stage sensor. In optimal conditions, an opportune installation of the seismic sensor might even grant an anticipation of more than one minute. This might be particularly useful if a warning system needs to be installed for the protection of a transport route (a road, a railway, a motor way) and it is impossible to install the system far enough upstream to provide sufficient warning. This situation may arise due to steep slopes, environmental conditions which may destroy the sensors or simply where maintenance of the system is too difficult.

A prompt warning would be needed to activate a traffic light and thereby impede the access to the endangered segment of the transport route. The early detection of the debris flow phenomena that the ground vibration detectors appear to provide, however, might be affected by the method adopted for the processing of the signal. This issue will therefore be explored and discussed in the following. The purpose is to provide new elements towards the standardization of debris flow warning issued through seismic and also other types of devices.

3. METHODS OF DATA PROCESSING

There are different methods that can be employed to process the seismic signal derived from a ground vibration sensor. Two well-known methods for processing seismic signals in debris flow monitoring are the amplitude method and the impulse method [*Arattano et al.*, 2014]. The amplitude method consists in calculating the mean of the signal absolute values over an interval of 1 second:

$$A = \frac{\sum_{i=1}^{F} |v_i|}{F} \tag{1}$$

The impulse method can be defined, instead, as the transformation of the raw geophone signal into a simplified impulse signal defined by when the geophone signal exceeds an empirically determined threshold (**Fig. 3**). The number of impulses per second and their duration is usually extracted from the analog signal with an electronic conditioning circuit board that is connected to each geophone [*Abancó et al.*, 2012]. Details regarding the application of the two methods can be found in literature [*Marchi et al.*, 2002; *Hürlimann et al.*, 2013]. In the following we will concentrate on the effects of the application of these two methods on the early detection of debris flows.

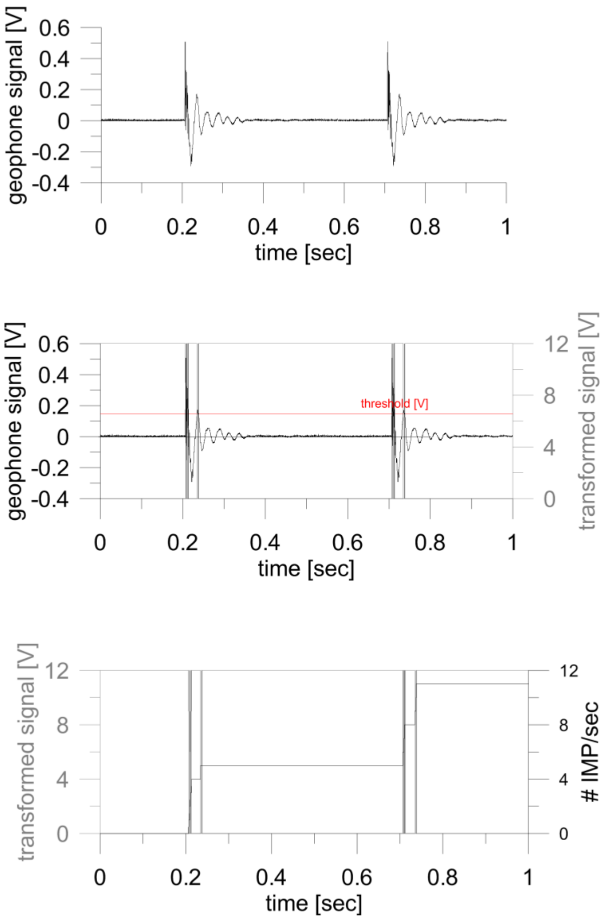

Fig. 3 Signal transformation from the detection to the recording with the impulses method: the geophone signal (above), the signal conditioner transformation (in the middle) and the datalogger input (below).

4. EFFECTS OF DATA PROCESSING ON DEBRIS FLOWS EARLY DETECTION

In **Fig. 4** the ground vibration data are shown that were recorded by a vertical geophone during a debris-flow event that occurred in the Rebaixader basin on July 4, 2012. In the first row the raw data are shown as they were directly obtained from the sensors. In the second row the graph is shown of the amplitude of the signal calculated on the basis of the raw data. Finally, in the following three rows, three curves of the impulses are shown that were produced applying three different threshold values.

In the last three rows of **Fig. 4** it is clearly visible the effect of the choice of the threshold on the ability to recognize the form of the debris flow wave through the impulse method. If the threshold is too low the graph of the impulses first suddenly rises at the arrival of the flow and then appears completely flat after the front has passed by [*Abancó et al.*, 2014]. The adoption of a higher threshold might avoid a flat graph and start depicting the form of the debris flow wave, but the threshold may remain still too low to reveal the different dimensions of the eventual surges that compose it. The proportionality between the different surges observed in the amplitude vs time graphs might be revealed through the method of impulses only adopting specific thresholds for each seismic trace, as shown in the last row of **Fig. 4**.

These aspects had already been noted by [*Arattano et al.*, 2014]. However, examining **Fig. 3** there is another important element that is influenced by the choice of the threshold. In fact the adoption of the lower threshold determines a rise of the curve of the number of impulses per second that starts much earlier and is much more evident than all the remaining graphs, including that of the amplitude.

This latter feature can be particularly important for the application of warning algorithms. As proposed by [*Badoux et al.*, 2008] an algorithm for the detection of debris flows might be based on the occurrence of a predefined number of impulses per second that last for more than a pre-established number of seconds. The number of impulses depends mainly on the threshold chosen for their counting, on the distance of the sensor from the torrent, and on the method of installation of the sensor. In this case the adoption of the lowest threshold might allow the detection of the debris flow and issue the alarm several seconds before than the other possible thresholds and also earlier than using the amplitude data. It must be noticed, however, that the gain in detecting earlier the debris flow occurrence is accompanied by a loss of information regarding the wave form of the debris flow and also the difference of magnitude of the different surges that comprise it.

From the analysis of **Fig. 4** the impulse method for warning purposes would conflict with its use for monitoring purposes: separate thresholds should be adopted according to the purpose pursued. However the graphs of **Fig. 5** seem to show that this is not always the case. In the first column of **Fig. 5** the ground vibration data are shown that were recorded along the vertical axe of a tri-axial geophone during a debris flow event that occurred in the Illgraben basin on July 27, 2009. It must be noticed that those data have been sampled at a frequency of 2000 Hz. While also in this case the choice of a higher threshold seems to affect the form of the graph of impulses, better revealing the debris wave form, it does not seem to particularly delay the detection of the debris flow arrival.

This is probably due to the presence of a much higher and significant background noise preceding the occurrence of the debris flow. This background noise and its greater intensity is particularly evident

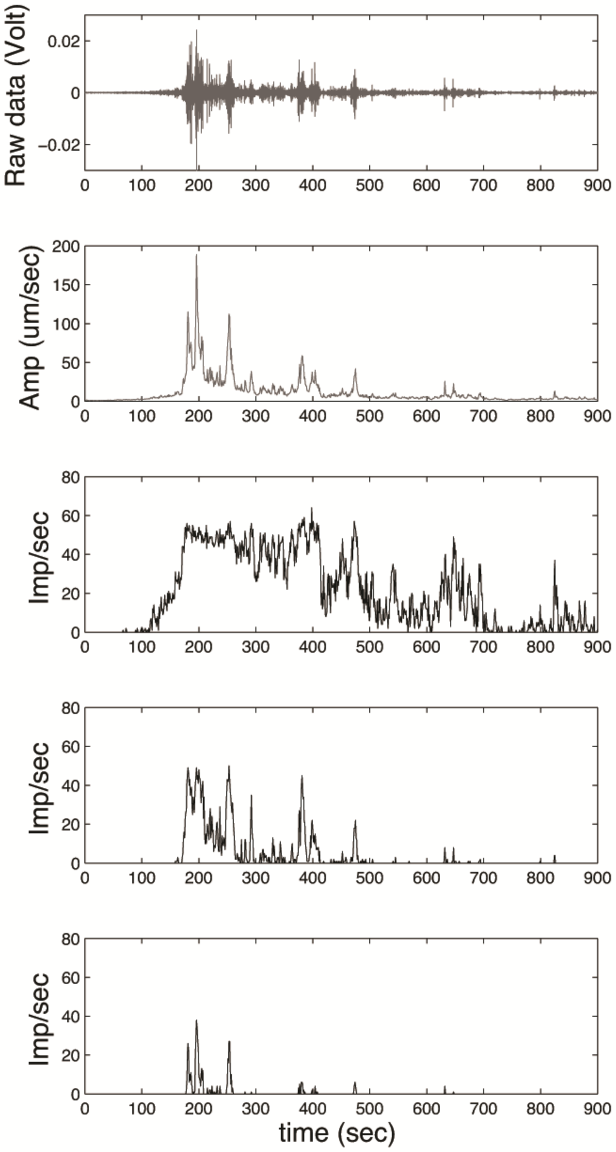

Fig. 4 Raw data (sampling rate = 250 Hz) recorded by a vertical geophone (first row), Amplitude graph (second row) and Impulses curves produced applying different threshold values (0.01 mm/sec in the third row, 0.05 mm/sec in the fourth row and 0.15 in the fifth row) of the debris flow event occurred in the Rebaixader basin on July 4, 2012.

comparing the raw data shown in the first row of **Fig. 5** with those shown in the first row of **Fig. 4**. This background noise is probably due to intense torrential activity (e.g. sediment transport during a flood) that preceded the arrival of the debris flow. The noise may have masked and covered the earlier inception of the rise of the number of impulses (third row of **Fig. 5**).

5. EFFECTS OF THE SAMPLING FREQUENCY

Another aspect that may be important for warning is the effect of the sampling frequency on data processing. When the raw geophone data are processed using the impulse method the result may be strongly affected by the sampling frequency adopted to collect the raw data. This might be particularly important if the results of the processing are used for warning purposes, as it will be illustrated in this section. In **Fig. 5** the data recorded in the Illgraben catchment on July 27, 2009 are depicted after re-sampling at 250 Hz. As expected the re-sampling significantly affects the number of impulses. For a sampling frequency of 2000 Hz, when the lowest threshold is adopted, the peak at the passage of the main front reaches almost 400 IMP/sec; for a sampling frequency of 250 Hz the peak reaches a value of only 60 IMP/sec. This effect, due to the digital transformation of the raw signal (sampled at a certain frequency) into impulses, might disappear if a signal conditioner were used that recorded the signal impulses. If the algorithm adopted for the detection of debris flows is based on the occurrence of a predefined number of impulses per second as mentioned earlier [*Badoux et al.*, 2008], this effect should be taken into account.

The choice of the predefined number of impulses per second needed to issue the alarm will in fact depend not only on the threshold chosen for counting the impulses, on the distance of the sensor from the torrent and on its method of installation, but also on the sampling frequency adopted. On the contrary, the amplitude graph does not show any particular change with the value of the sampling frequency and so it would appear to be the easier and more robust method to apply for warning. However, in case a greater anticipation of the detection is needed, an investigation of the performance of the method of impulses might be attempted to verify the performance.

The main reason why the signal sampled at 250-Hz produces such a decrease of the number of impulses appears clear from the exam of **Fig. 6**. In this figure, two seconds of seismic recordings extracted from the signal sampled at 2 kHz and then sub–sampled at 250 Hz are enlarged and the amplitude spectra of two separate time windows are calculated. The graph of the amplitude spectra of the first time window shows a peak around 250 Hz in the signal sampled at 2 kHz that is lost in the signal sub–sampled at 250 Hz. In this case the number of impulses calculated on the signal sampled at 250 Hz will be inevitably lower. On the contrary the graph of the amplitude spectra of the second time window shows a peak around 20 Hz in the signal sampled at 2 kHz that is also visible in the signal sub–sampled at 250 Hz. For this time

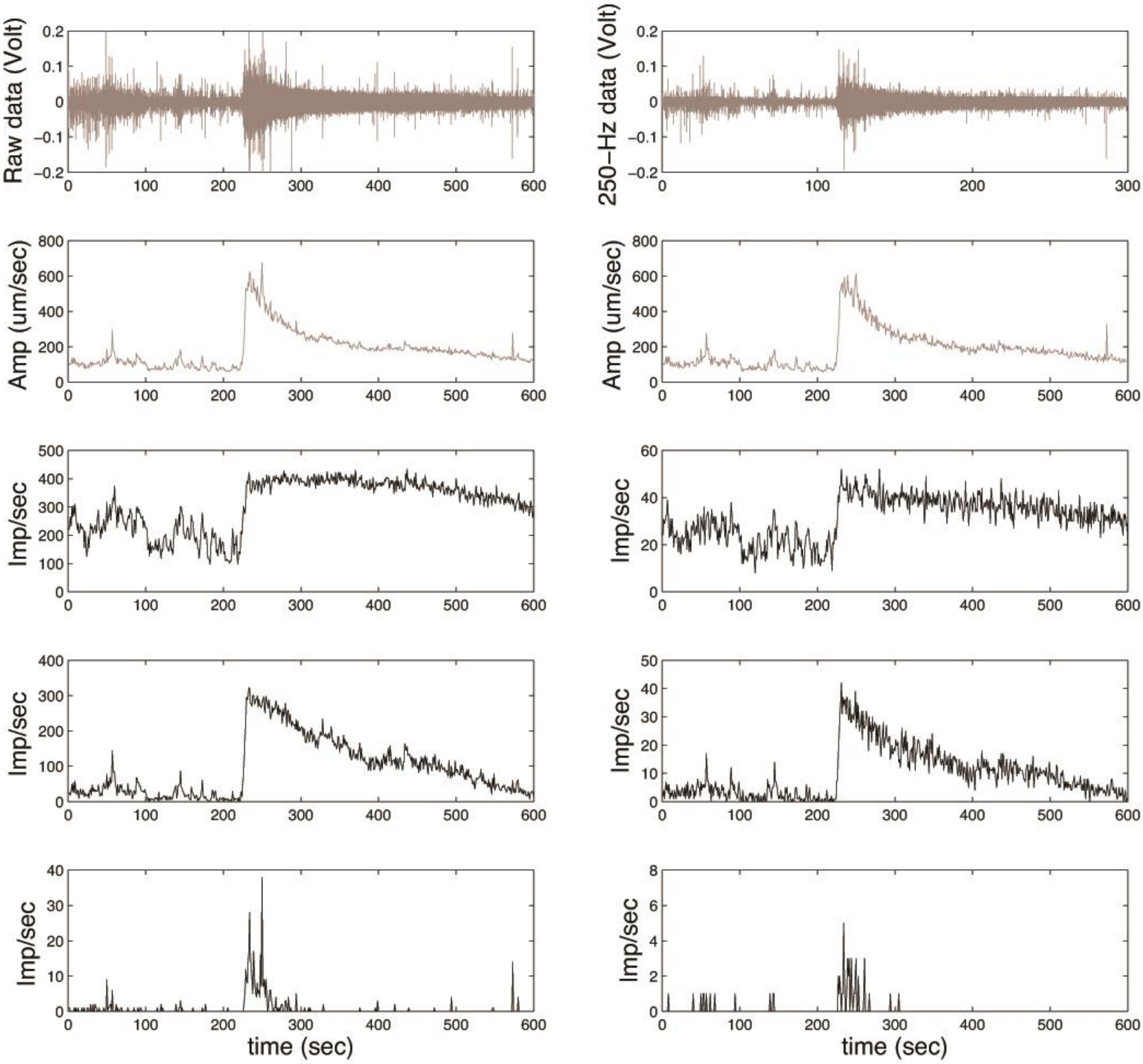

Fig. 5 First row: vertical component of the raw data (sampling rate = 2000 Hz) and sub-sampled data at 250 Hz of the debris flow event occurred on July 27, 2009 at Illgraben recorded by a triaxial geophone installed in the ground; second row: amplitude graphs; following rows: impulses curves produced applying different thresholds (0.035 mm/sec in the third row, 0.35 mm/sec in the fourth row and 1.8 mm/sec in the fifth row).

window the difference between the number of impulses calculated at 2 kHz and at 250 Hz will be certainly smaller. This means that the debris flow signal may present portions of the signal with very high frequencies that may significantly influence the counting of impulses if sampled at lower sampling rate [*Coviello*, 2015].

6. CONCLUSIONS

Two well known seismic data processing methods were compared in this paper, to improve the knowledge on debris flow warning through seismic devices. Both methods are suitable for debris flow early detection. Effects of the different data processing methods on debris flow early detection are the following:

- the application of the amplitude method does not affect the capabilities of debris flow early detection, on the contrary, the choice of the threshold in the impulses methodology might;
- applying the impulses method, too low thresholds provide too little information on the debris flow generation and evolution because it may result in a flat graph;
- higher thresholds deliver better information on the shape of the debris flow surges, but delay the rise of the curve resulting in a less effective

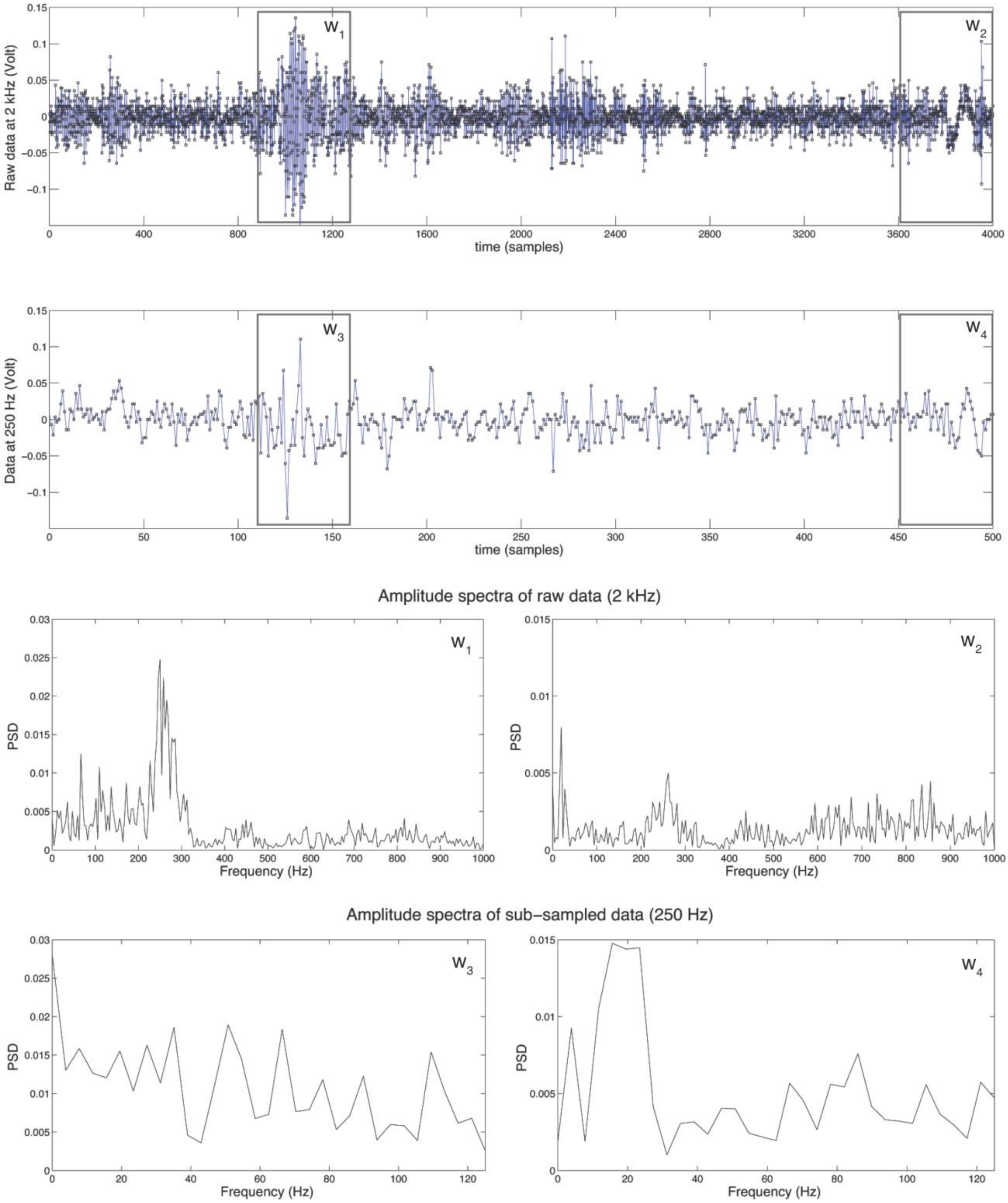

Fig. 6 Above, two seconds of recording of the debris flow occurred on July 27, 2009 in the Illgraben basin: raw data (sampled at 2 kHz) and sub-sampled data at 250 Hz. Below, the amplitude spectra of two time windows per trace, extracted both from the 2-kHz signal (w_1 and w_2) and from the 250-Hz signal (w_3 and w_4). Image after [*Coviello*, 2015].

early detection;

- the use of the method of impulses for warning purposes would conflict with its use for monitoring purposes: separate thresholds should be adopted according to the purpose of the monitoring.

There seem to be also some effects deriving from the sampling frequency adopted: the amplitude method does not show any particular change based on the sampling frequency while the transformation of the raw signal (sampled at a certain frequency) into impulses method does.

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