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Analysis of the ground vibration produced by debris flows and other torrential processes at the Rebaixader monitoring site (Central Pyrenees, Spain)

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Abstract

The use of ground vibration sensors for debris-flow monitoring has increased in the last two decades. However, the correct interpretation of the seismic signals produced by debris flows still presents many uncertainties. In the Rebaixader monitoring site (Central Pyrenees, Spain) two different ground vibration stations with different characteristics in terms of recording systems and site-specific factors have been compared. The shape of the time series has been recognised as one of the key parameters to identify events and to distinguish between different types of torrential processes. The results show that the site-specific factors strongly influence on the ground vibration registered at each geophone. The attenuation of the signal with the distance has been identified as linear to exponential. In addition, the assembly of the geophones to the terrain also has an important effect on the amplification of the signal. All these results highlight that the definition of ground vibration thresholds for debris-flow detection or warning purposes is a difficult task which is clearly influenced by site-specific conditions of the geophones.

1 Introduction

Debris flows are one of the most hazardous geomorphologic processes. In order to improve the understanding of debris-flow mechanisms, torrents are being instrumented with an increasing variety of sensors. The data collected by the sensors are not only needed to calibrate numerical models, but also to develop and adjust warning systems.

Although debris-flows monitoring has strongly improved during the last decades and several torrential catchments in the world have been instrumented with different types of sensors and techniques (http://www.unibz.it/en/sciencetechnology/welcome/monitoringbedloadanddebrisflowsinmountainbasins.html), this is still a challenging topic in debris-flow research. Besides debris flows, monitoring is also used for the analysis of other types of rapid mass movements like snow avalanches or rockfalls

(Suriñach et al., 2005; Bessason et al., 2007; Vilajosana et al., 2008) and bedload transport in rivers and torrents (Rickenmann et al., 1998, 2012). Torrential processes, especially debris flows, generate seismic waves in the ground, originated by the collision between boulders or between boulders and the bedrock. These vibrations can be measured by several seismic and sonic devices (such as geophones, seismographs or infrasounds; Kogelnig et al., 2011a; Itakura et al., 2005). Geophones are the most common seismic sensors used in debris-flow monitoring because of their robustness and low power consumption. These features make them also very suitable not only for monitoring, but also for warning purposes. All over the world, several sites have been instrumented with geophones: Illgraben in Switzerland (Hürlimann et al., 2003), Lattenbach in Austria (Kogelnig et al., 2011a), Moscardo (Arattano et al., 2012), Acquabona (Berti et al., 2000) or Gadria (Marchi et al., 2012) in Italy, Manival or Réal in France (Navratil et al., 2011), Mount St Helens in USA (LaHusen, 2005b), Houyenshan (Chou et al., 2010), Fong-Ciou Creek or Ai-Yu-Zi Creek (Huang et al., 2007; Fang et al., 2011) in Taiwan, and Jiangjia in China (Cui et al., 2005) are some examples.

Some analyses of geophone signals induced by debris flows have been published during the last decades (Arattano et al., 2012; Huang et al., 2007; Arattano and Moia, 1999; Chou et al., 2010; Berti et al., 2000; Hürlimann et al., 2003). All these studies have substantially increased our knowledge on the dynamic behaviour of debris flows and the ground vibration they induce. However, there are still many open questions, such as the use of the ground vibration for the definition of thresholds for detection or warning or the distinction between different flow types (e.g. debris flow vs. debris floods).

The ground velocity signal can be recorded by two different approaches: (a) continuously (e.g. in Moscardo torrent; e.g. Arattano and Moia, 1999); and, (b) by switching from a no-event mode into an event-mode (e.g. in the Swiss torrents; Hürlimann et al., 2003). The latter approach needs the incorporation of a trigger into the recording algorithm and the correct definition of its value. Different types of triggers can be found in the literature: (a) level triggers: fixed value of the ground

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velocity (LaHusen, 2005a); or fixed values of a transformed signal (Badoux et al., 2009; Hürlimann et al., 2011); (b) more sophisticated thresholds based on the frequency content of the signal (Bessason et al., 2007). The type of threshold mainly depends on the data recording system implemented at the site. Several systems have been used historically: (a) analogical recording (Arattano and Moia, 1999), (b) digital sampling (Arattano, 2000; Kogelnig et al., 2011b); and, (c) transformations of ground vibration velocity signal (Navratil et al., 2011; Abancó et al., 2012).

Normally, the threshold value (level triggers) is established combining an empirical analysis of the signals of past events and expert criteria. The threshold has to be defined at each geophone, as there are several site-specific factors that influence the vibration recorded at the seismic sensors. An accurate assessment of the threshold is of crucial importance; especially in warning systems, when the detection of events triggers some kind of alarm process, such as the closing of traffic lines or messages to the stakeholders. However, there are only very few studies dealing with the influence of the site-specific factors affecting the vibration induced by debris-flow events (Navratil et al., 2011; Huang et al., 2007).

In this paper the features of the ground vibration signals registered at two monitoring stations located in the Rebaixader monitoring site are analysed. The main difference between the two stations is the data recording system, but also some other aspects regarding the mounting and the location of the geophones. The major purpose of this work is to define the main characteristics of debris flows and other torrential processes using the seismic data recorded at the two stations (different data recording systems) installed in the site. Other objectives are the analysis of the influence of some site-specific factors on the ground vibration signal by means of field test and a sensibility analysis of the threshold values. The outcomes of this research improve the knowledge on some current issues (i.e., process differentiation, geophone location, recording method or threshold assessment) and should help for the set-up of future debris-flow monitoring or warning systems.

2 Debris flow characterization by ground vibration monitoring

2.1 Debris-flow features

Debris flows are rapid landslides formed by water and solid material poorly sorted, from boulder to clay (Iverson, 1997). Pierson (1986) describes a typical debris flow by three parts: the front, the fully developed debris flow (also called “body”) and the tail. The front carries the biggest boulders and is followed by the debris flow body, with a high sediment concentration, in a turbulent regime. At last, there is the tail with much less solid material concentration, which can also be characterised as a hyperconcentrated flow. Many debris-flow events occur in a series of surges, each one showing a front, a body and a tail (Pierson, 1986; Johnson and Rodine, 1984).

The coexistence of torrential processes has been noted in the Rebaixader site. Debris floods can be defined as episodes of massive bedload transport, characterized by a limited maximum grain size (Aulitzky, 1982). Debris floods are also described as very rapid surging flows of water in a steep channel, heavily charged with debris (Hungr et al., 2001). A debris flood may transport quantities of sediment comparable to a debris flow, in the form of massive surges. However, the transport is carried out by the tractive forces of water overlying the debris. As a result, the peak discharge of a debris flood is comparable to that of a water flood (perhaps multiplied by a factor up to 2). This fact clearly contrasts with the peak discharges of debris flows, which are tens of times greater than major water floods (VanDine, 1985; Hungr et al., 2001). Another important difference between debris flows and debris floods is the absence of the bouldery front.

Ground vibration produced during the pass of a debris flow has its origin in the impacts between boulders or between boulders and the channel bed. A change of sediment concentration and boulder content alters the energy transmitted to the ground as seismic waves in such a way that debris flows can be distinguished from other torrential processes, but also parts of a debris flow and surges (Huang et al., 2007).

2.2 Monitoring of debris-flow induced ground vibration

Velocity of ground movement is transduced by a geophone to a voltage that is (generally linearly) related to the ground velocity. The digital measuring of the geophone output is done by sampling the signal with a certain frequency. To avoid aliasing problems, the sampling rate must be greater than the Nyquist frequency, which is twice the highest frequency of the signal. Digital sampling is used to record the data from the geophones, but also other techniques based on the transformation of the original signal into simpler data have been developed. These data recording systems are widely described in the following sections.

Several features of moving debris flows have been estimated analysing ground vibrations. For instance, the correspondence between the hydrograph and the ground velocity signal (Arattano and Moia, 1999), or the increase of the amplitude of the ground vibration as the flow front approach to the seismic sensor (Arattano et al., 1999). Furthermore, the flow volume was correlated with the time integral of the acceleration amplitude (Suwa et al., 2000). Other authors found some general patterns in the frequency domain. For instance, LaHusen (1996) described the typical peak frequency range of the debris flows between 30 and 80 Hz, or Huang et al. (2007) suggested this range from 50 to 100 Hz.

2.3 Ground vibration site-specific factors

Both the amplitude and frequency of the signal measured by the geophones depend on several site-specific factors. The influencing factors considered herein are the distance between the sensor and the debris-flow path, the material in the channel and channel-banks and the assembly of the geophone.

Geophones are generally installed outside the channel bed, in a protected location, to avoid damage when a torrential event occurs. However, waves are attenuated with the distance and they do not travel long distances (LaHusen, 2005b). For this reason, the distance between sensor and flow path is a crucial factor and geophones are commonly installed not further than few tens of meters from the active channel or on its lateral banks.

The attenuation of the seismic waves depends on the properties of the material the wave travels through. Depending on the material, the absorption of the energy by the ground is higher or lower (Itakura et al., 2000; Biescas et al., 2003; Suriñach et al., 2001). Also the physical properties of the transmission medium conditions the velocity of the waves. For example, P wave velocity ranges from about 350 m s^{-1} in alluvium up to 700 m s^{-1} in bedrock (Arattano and Moia, 1999).

When geophones cannot be buried in soil, the sensors must be fixed to the bedrock, big boulders or existing concrete structures (e.g. check dams). In this case, the method of fixing the geophones to these hard surfaces controls the transfer of vibrations to the sensor and, consequently, has a strong influence on the signal recorded. Since the surfaces are often irregular, different assembly systems are designed in the existing monitoring stations (Abancó et al., 2012). The assembly structures can show a resilient vibration, therefore affecting and conditioning the signal registered.

3 Description of the Rebaixader site

3.1 General setting

The Rebaixader catchment is a first order basin with an extension of 0.53 km^2, which is located at the Central Pyrenees near the village of Senet (Fig. 1). The catchment has the typical morphology of a torrential basin formed by three zones (erosional source area, channel zone and fan). The source area has a steep slope (average of 29°, but up to 50°), an extension of 0.09 km^2 and it is located between 1425 and 1710 m a.s.l. (Fig. 1). The channel zone has an average slope of 21°, is 250 m long and about 20 m wide and is located between 1425 and 1350 m a.s.l. Downstream the channel zone, there is a fan with an area of 0.082 km^2 and a mean slope of 17°. The Noguera

Ribagorçana River defines the lower boundary of the fan. There is no protection works in the Rebaixader torrent.

The geology of the source zone consists of a thick till deposit over bedrock of slates and phyllites of Devonian age. The bedrock crops only locally out in the source and forms the margins of the channel zone. The till corresponds to a lateral moraine of the glacier that occupied the Noguera Ribargorçana Valley during the Last Glacial Cicle (Vilaplana, 1983).

The meteorological conditions of the site are affected by the proximity of the Mediterranean Sea, the influence of the Northern-Atlantic winds and the orographic effects of the Pyrenees. The debris flows and debris floods analysed in this study are mostly triggered by convective storms in the summer, which are characterised by short and intense rainfalls (Hürlimann et al., 2011), but it has recently observed that also rainfalls of lower intensities occurred in spring, accompanied by snowmelt, can also trigger events.

3.2 Monitoring network

The monitoring system installed in the Rebaixader torrent includes, on one side, four stations measuring the meteorological and hydrological conditions in the catchment for the analysis of the debris-flow initiation and, on the other side, two stations regarding the detection and characterisation of the flow dynamics. Further details about the instrumentation can be found in Hürlimann et al. (2011). Herein, we focus on the two stations measuring the ground vibration (FLOW-WR and FLOW-SPI in Fig. 1) to characterise the flow dynamics. The geophones of both stations are 1-D vertical, moving coil geophones (Geospace 20-DX) with a natural frequency of 8 Hz and a spurious frequency of 200 Hz. The main difference between the stations is the data recording system. The data acquisition in station FLOW-WR is based on a low sampling rate of a transformed signal, meanwhile in station FLOW-SPI the high sampling rate provides data on the original ground velocity signal.

The station FLOW-WR includes five geophones, an ultrasonic device for stage measurements and a video camera. The sensors are connected by wires and controlled by a Campbell CR1000 datalogger, which is powered by a 12 V 24 Ah battery, charged by a 30 W solar panel. The data are transmitted via GSM modem to our server in Barcelona. The geophones are distributed along 175 m at the right side of the torrent (Figs. 1 and 2a), between 1415 and 1345 m a.s.l. The distances between geophones are up to 75 m, and the distances between the sensors and the active channel range from 8 to 25 m (Table 1). Four of the five geophones are mounted by a metal sheet box to the bedrock (geophones Geo1–Geo4 in Fig. 2b). Each box is protected by a plastic structure in order to avoid the impact of raindrops or hail on it. The 5th geophone (Geo3b) is fixed directly on the bedrock without a metal box. It is also protected by a plastic structure like the other geophones.

The station FLOW-SPI was set up in June 2012 in order to record the ground vibration by an additional method. The station contains three geophones, which are located at the left side of the channel (Figs. 1 and 2a). The geophones are located between 3 and 5 m from the active channel, thus much closer than those of the station FLOW-WR (Table 1). At this station, all the geophones are fixed directly to the ground. Two of them (geophones Geo6 and Geo7) are buried in the soil (granular colluvium) at a depth of about 20 cm (Fig. 2d), while the third one (Geo5) is fixed to the bedrock (Fig. 2c) and protected by a plastic structure by the same system as in the other station. Data logging is carried out by a 24 bits broadband seismic recording unit (Spider, manufactured by Worldsensing s.l.), powered by a battery of 12 V, 22 Ah, and charged by a 50 W solar panel. The Spider sends the data to a gateway, where they are resent to our server via GSM modem.

4 Analysis of transformed Ground Velocity Signal

4.1 Methods

The data recording system at the FLOW-WR station is based on the transformation of the original signal, a voltage signal proportional to the ground velocity, into a signal consisting in impulses per second (Abancó et al., 2012). The signal transformation is carried out by an electronic conditioning circuit board that is connected to each geophone (Fig. 2b). The aim of the transformation is twofold: (a) it filters and deletes the ground vibration noise, and (b) the impulses per second (IS) data constitute a simple discretised signal, which can be analysed more easily and with lower memory requirements.

The procedure of signal transformation involves two parts: (1) the filtering, and (2) the conversion to impulses. Firstly, the original voltage delivered by the geophone is filtered to remove low ground velocities, which are assumed to correspond to noise. This filtering is made analogically by a set of electrical resistors in the conditioning circuit board, which act like a threshold voltage. At Rebaixader site, we use two types of electrical resistors and thus two values of "ground velocity threshold" (GVth) depending on the geophone assembly. For the geophones mounted in a metal sheet box (Geo1, Geo2, Geo3, Geo4), the threshold corresponds to a velocity of $0.17\,\mathrm{mm\,s^{-1}}$. The other geophone (Geo3b), which was fixed directly to the bedrock and no resonance effect of the metal box is expected, the velocity threshold is much lower ($\mathrm{GVth} = 0.019\,\mathrm{mm\,s^{-1}}$). After this filtering, the signal is transformed into impulses per second by the conditioning circuit (for further details, see Abancó et al., 2012).

The frequency of measuring is controlled by the CR1000 datalogger, which was programmed to scan the geophones of the station every second. To avoid high power consumption and to optimize the memory management of the data files, an algorithm was introduced into the CR1000 datalogger and the recording is not carried out continuously, but only when the number of impulses per second exceeds a threshold. This threshold is called "event mode threshold" (EMth) and is based on the number of impulses per second cumulated during a certain time span (Fig. 3). Therefore, this "event mode threshold" includes two components: (a) the "number of impulses of the EMth" ($\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$), and (b) the "duration of the time span in which $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ is exceeded" ($\mathrm{EMth}_{\mathrm{dur}}$). The event mode threshold was defined progressively by analysing the data of the 1st year of the monitoring period. Since August 2010, the $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ was fixed at 20 impulses per second ($\mathrm{IMP\,s^{-1}}$) and the $\mathrm{EMth}_{\mathrm{dur}}$ was established as three consecutive seconds. When the threshold is exceeded in any of the geophones of the station, the "event mode" is triggered by the datalogger code and the signal is recorded each second. Event mode is deactivated after 2 min with vibration smaller than $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ scanned in any of the geophones. The recording is also carried out during the "no event mode" to monitor the noise and the performance of the system; although at a much lower frequency (each hour).

As it is shown below, several types of events (debris flows, debris floods and rockfalls) were recorded in the Rebaixader torrent. The analysis of the IS times series revealed different types of responses (IS curve morphologies). Finally, these IS curve morphologies were assigned to different types of torrential processes by means of cross-checking the vibration gathered in the five geophones, the flow depth measured by the ultrasonic device, the video images (available only for 10 events) and periodic field trips (31 campaigns), carried out after most of the events to identify geomorphic changes in the site.

4.2 Results

Between August 2009 and December 2012, the "event mode" was triggered 363 times. The trigger was mostly (216 times) provoked by malfunctions in one of the geophones, which was affected by a rockfall in 2010 (Hürlimann et al., 2012). Another 126 triggers were attributed to small mass movements at the lower part of the scarp area, that did not progress downstream, as it was observed during periodic field reconnaissance carried out, which indicated no apparent geomorphic changes in the channel reach after some of these triggers. Consequently, 342 of the 363 events were not considered as significant torrential events and were classified as "other triggers", including both the malfunctions and the small movements that triggered the system. Indeed, the EMth was calibrated during the first monitoring year to minimise the recording of this type of triggers.

For the whole monitoring period, 21 torrential events were recorded by the station. Regarding the shape of the IS time series curve, three types of curves were distinguished (Fig. 4).

Type A curve is characterised by three phases (Fig. 4a): (a) a first phase of stationary level of no or very low IS values, (b) an abrupt increase of the impulses, reaching values over 100 IMP s^{-1} in less than 5 s, followed by (c) a slow (mostly exponential) decrease.

Type B curve consists of a first phase of gradual increase of IS-values, which is followed by a gradual decrease (Fig. 4b).

Type C curve is defined by a very short duration (2–5 s) fast increase of the IS-values, with a high maximum (up to 190 IMP s^{-1}; Fig. 4c).

Video images and geomorphological reconnaissance clearly showed that A-curves were recorded during debris-flow events (Fig. 5b, d, f and h); B-curve was associated with debris floods or immature phases of debris flows, and C-curves were related to rockfalls (Hürlimann et al., 2012). However, only Geo4 recorded A-curves for all the debris flows. The time series recorded at the upper geophones show other types of curves, different than A-curve, especially during the "small-magnitude" debris flows (Fig. 5a and e). It is interpreted that debris flows generate A-curves, but the former facts suggest that only when the flow reach the location of Geo4 debris flows are fully developed, showing a well-defined front. It should be noted that geophones 1–3 are located at greater distances from the active channel (15–25 m) than Geo4 (8 m) and the attenuation of the vibration with distance may probably play a role in the recordings of debris flows by geophones more distant from the flow path, as it is shown below. Besides the shape of the curve, the peak of IMP s^{-1} time series at Geo4 is useful to distinguish between debris flows and debris floods. The values of peak vibration in this geophone never exceeded 100 IMP s^{-1} for debris floods, while the values are from

130 up to 211 IMP s^{-1} for debris flows. Highest values of vibration corresponding to rockfalls and the shortest durations of vibration were recorded in Geo1, the uppermost geophone.

Most of the records in Fig. 4 present similar durations. In general, the flow events (debris flows and debris floods) last several hundreds of seconds, around 10 min. Exceptionally, the debris-flow event registered on 11 July 2010 lasted approximately 10 times this common value. An unusually long-lasting and high intensity rainfall event ($\sim 50\,\mathrm{mm\,h^{-1}}$ as peak hourly rainfall intensity and more than 3 h of duration) accompanied this debris flow and generated many flow surges. Therefore, except this July 2010 event, the registers suggest that there are no differences between debris flows and debris floods in terms of duration of the IS signal.

5 Analysis of original Ground Velocity Signal

5.1 Methods

At the station FLOW-SPI, the geophone signal is recorded directly as a voltage and represents the vertical velocity of ground vibration. The data provided by FLOW-SPI station differ from the FLOW-WR station in two main points: (a) the recording of the ground velocity signal (GVS) is continuous without distinction between “event” and “no event” modes; and, (b) the signal is recorded without filtering the noise. The data are stored in “mseed” files, a typically seismological format. Each of these files contain approximately 30 min of data sampled at 250 Hz (250 samples s^{-1}).

The sampling frequency depends on the nature of the process and the site-specific characteristics of the geophones and their placement. Preliminary spectral analyses of some flow events in the Rebaixader catchment indicated frequency ranges between 30 and 100 Hz. Therefore, a sampling frequency of 250 Hz is sufficient in this case..

FLOW-SPI station was installed in 2012, and for this reason only three events were recorded. Due to the small number of events, the distinction between types of events or their features by a detailed GVS analysis (as performed for the IS time series) was

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not possible due to the limited number of events. Video images were available only for one of the events because the first two events occurred at night and the infrared spot lights were damaged by an unexpected large debris flow. Thus, the interpretation of the GVS signals recorded during the events was carried out mainly by cross-checking the data from both stations (FLOW-WR and FLOW-SPI), by analysing the flow depth recorded at the ultrasonic device, which is located very close to the three geophones of FLOW-SPI station (Fig. 1), and by information obtained from the field reconnaissance.

5.2 Results

The GVS recorded during the events shows different phases that define the progression of the flowing mass over time:

(a) Phase 0 (P.0) is a pre-event phase, characterized by stationary low values of GVS and also low stage measured at the ultrasonic device.

(b) Phase 1 (P.1) is characterized by a rapid increase of the values of the GVS as well as the flow stage and corresponds to the pass of the debris-flow main front(s).

(c) Phase 2 (P.2) is defined by GVS values lower than the flow front, but some peaks are still visible as well as punctual flow-depth increases. This phase is related to the passing of the main body of the flow.

(d) Phase 3 (P.3) includes a gradual decrease of GVS and stage measurements back to the pre-front values of P.0. However, some small increments can still be observed. This last phase is interpreted as corresponding to the flow tail.

Phase 0 was observed in all of the events (Fig. 6a–c). Typical values of the ground velocity for phase 0 are less than $0.005\,\mathrm{mm\,s^{-1}}$ and are about 100 times lower than the highest value of the signal during debris flows and 4 times lower during the debris flood. For all the geophones and events, these values represent between ~ 1 (for debris flows) and 25 % (for debris floods) of the highest peak of the event signal. Phase 1 (“front”) was only visible in the large debris flow (Fig. 6a). The GVS records of this phase are the highest ones of the event, up to 1.6 mm s^{-1} (at Geo7). The duration of Phase 1 was short compared to the other phases (only ∼ 40 s).

Phase 2 (“main body”) was observed in the three events and it is characterized by high values of vibration compared to Phase 0 and Phase 3, although lower than Phase 1. Typical values are of some tenths of mm s^{-1} for debris flows and lower for the debris flood. The duration of this phase was similar in the three events (∼ 100 s).

Phase 3 is characterized by low values of vibration, but some peaks could be observed (see the event of 27 June, where the highest peak at Geo5 was recorded during Phase 3. An explanation of these peaks may be related to the passing of some boulders or small waves in spite of the global decrease of vibration and discharge.

The comparison between the three geophones suggests that Geo5 (installed on bedrock) provides a clearer signal. This observation especially fits for the small-magnitude events, while for the very large debris flow the three geophones present similar characteristics.

6 Effects of site-specific factors

The vibration registered by the geophones in both seismic stations of the Rebaixader torrent is conditioned by different aspects. Some factors such as the distance to the flow path, the underground material, the assembly of the geophones or the ground vibration threshold used in FLOW-WR will be studied and discussed in this section.

6.1 Distance and underground material (field tests)

In summer 2012, we carried out some field tests at station FLOW-SPI in order to record the GVS under specific conditions. We released a 9 kg sledgehammer from a height of 1.5 m at different distances (0–20 m) from the three geophones Geo5, Geo6 and Geo7 along the corresponding cross-section of the torrent. We performed the tests mostly twice to improve data quality. Similar tests have also been performed in other studies (Navratil et al., 2011; Kogelnig et al., 2011b).

The results showed that the highest amplitudes were recorded in geophone Geo6, which is buried into a thin layer (< 50 cm) of colluvium (Fig. 7). Geophone Geo5 (fixed to the bedrock) shows larger amplitudes than Geo7 (buried into thicker soil layer, > 2 m), however they are more than one order of magnitude lower than in Geo6. In terms of attenuation with distance, Geo5 and Geo6 show similar exponential trends, while Geo7 shows a considerably lower attenuation, following a linear trend.

These results do not completely fit with the results of previous section, where the maximum amplitudes were registered at Geo5. For this reason, they can be considered as experimental results that demonstrate the variations of similar signals recorded at geophones with different underground conditions. Nevertheless, the attenuation with distance is evident and can be observed at the three geophones.

6.2 Assembly and distance

In order to identify the influence of the assembly of the geophone and the distance to the flow path, the signal recorded at three different geophones (Geo3, Geo3b and Geo5) was compared. These three geophones were selected, because they are installed approximately at the same cross-section of the channel (Fig. 1). Geophones Geo3 and Geo3b are located at the right margin of the channel and very close together (they are only 50 cm apart). Geophone Geo5 is placed at the left margin of the channel, 35 m upstream from Geo3 and Geo3b. All of them are mounted on bedrock. Geo5 and Geo3b are fixed directly on bedrock and Geo3 is mounted in a metal sheet box, which is fixed to the bedrock.

As it was mentioned above, the signal at Geo5 is recorded directly as GVS. Thus, the Geo5 data were transformed into IS in order to be comparable with the data measured at Geo3 and Geo3b, which were recorded as IS signal. This transformation was carried out as a post-process by a MATLAB code (MATLAB, 2009). The code applies the same transformations to the GVS that is done by the signal conditioner of the FLOW-WR station. As a preliminary stage, a baseline correction was performed to avoid offsets derived from the analog-to-digital converter (ADC). Then, the GVS below a certain GVth is filtered and the GVS over the threshold is transformed into an IS signal. The GVth is applied by means of electrical resistors in the signal conditioner for Geo3 and Geo3b, but as an input variable of the MATLAB code for Geo5. The GVth values used for the transformation into IS are: 0.17 $\mathrm{mm\,s^{-1}}$ in Geo3 and 0.019 $\mathrm{mm\,s^{-1}}$ at Geo3b. It is worth noting that the GVth used for the transformation into impulses at Geo3b (which is fixed directly to bedrock) is 10 times lower than at Geo3 (which is mounted in a metal sheet box). IS time series from Geo5 were obtained for both threshold values (0.17 and 0.019 $\mathrm{mm\,s^{-1}}$). The comparison of the four resulting IS time series shows the influence of the distance and the effect of the metal sheet box. In Fig. 8 the ground vibration of the 4 July 2012 debris flow is presented for the three geophones: Geo3 (Fig. 8a), Geo3b (Fig. 8c) and Geo5 (Fig. 8b and d).

The results show that the metal sheet box has a strong amplification effect on the signal. The significant difference of the records of Geo3 and Geo3b can only be explained by the effect of the metal sheet box, which works as a resonant structure magnifying the vibration registered by the geophone. The influence of the metal sheet box produces an increase of the values of the IS signal at Geo3, up to 10 times higher than the ones measured at Geo3b. It is important to remind that the ground vibration threshold at Geo3 is 10 times greater than in Geo3b (GVth = 0.17 vs. 0.019 $\mathrm{mm\,s^{-1}}$, respectively). Thus, the results suggest that there is a large amplification of the vibration caused by the metal box.

The effect of the distance to the flow path can be noticed by comparing the data from Geo3b (Fig. 8c) and Geo5 (Fig. 8d). Both geophones are directly mounted on bedrock and the velocity threshold is the same in both cases (GVth = 0.019 $\mathrm{mm\,s^{-1}}$), while the distance between the geophones and the active channel is greatly different (25 m at Geo3b and 3 m at Geo5). To summarize, the influence of the box assembly and the distance greatly affect the IS signal registered at the geophones. Although an exact quantification of the effects is difficult, it can be stated that the influence of the metal sheet box generates an amplification of the signal more than what is attenuated by the effect of 20 m of distance.

6.3 Threshold definition for debris-flow detection

The most important point regarding the development of a reliable warning system is the definition of the detection threshold, in such a way that false alarms are reduced to a minimum. In the FLOW-WR station at the Rebaixader monitoring test site, we defined a "detection threshold" (Dth) for the monitoring system, calibrated for research purposes. The Dth is based on two thresholds: on one side the GVth, and on the other side the EMth, which is formed by $\mathrm{EMth}_{\mathrm{dur}}$ and $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ (see Sect. 4.1). As it is suggested by the results in previous sections, the site-specific factors influence the vibration recorded at each sensor, and the values recorded can be widely different from one geophone to another. For this reason, the values of GVth and EMth should be defined for each specific geophone, according its placement and assembly. This calibration has a crucial importance for warning systems, but since in the Rebaixader site the installation was intended to research purposes, the thresholds have been maintained constant and low for all the geophones.

Using the data from the debris flows occurred on 27 June 2012 and 4 July 2012, a sensibility analysis of the three Dth parameters was carried out. Different values of GVth and EMth were tested using data recorded by the geophones of FLOW-SPI station, where the complete register of the ground velocity signal was available (Geo5, Geo6, Geo7). First, the data were transformed into impulses using 10 different values of GVth. Then, two values of $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ (10 and 20) were chosen and the number of seconds over it was obtained for each GVth value and $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$. The number of seconds over $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ corresponds to the maximum value of $\mathrm{EMth}_{\mathrm{dur}}$ that could be defined for each combination of $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ and GVth in order to detect the debris flow.

Figure 9 reveals that the number of consecutive seconds that the signal exceeds the $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ exponentially decreases with increasing GVth for both values of $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ (10 and 20) and for both events. The change of $\mathrm{EMth}_{\mathrm{IMP\,s^{-1}}}$ from 10 to 20 IMP s^{-1} does not influence significantly, which suggests that the most important factor in Dth is the GVth.

It is worth noting that any of the debris flows would not have been detected for the Dth parameters used in the station FLOW-WR (GVth = 0.17 mm s^{-1}; EMth$_{\mathrm{IMP\,s^{-1}}}$ = 20; EMth$_{\mathrm{dur}}$ = 3). This fact enforces the outcomes of the previous section on the effect of the metal sheet box, which strongly amplifies the ground vibration. Assuming a GVth – value of 0.019 mm s^{-1} (as used at Geo3b, where there is no box), the big event (4 July) would have been detected by the three geophones, while the small event (27 June) would only have been detected by Geo5 and Geo6.

In conclusion, a reliable threshold should detect the desired events as early as possible, but filter the ground velocity that does not correspond to an event. The definition of an incorrect combination of the tree threshold parameters (EMth$_{\mathrm{dur}}$, EMth$_{\mathrm{IMP\,s^{-1}}}$ and GVth) could suppose missing an event, such as it can be observed for the data from the event of 27 June (Fig. 9a and b), where EMth$_{\mathrm{IMP\,s^{-1}}}$ was almost never exceeded.

From all these results, we propose that best configuration at the Rebaixader site, for the detection including small events, would be a GVth from 0.1 to 0.2 mm s^{-1}; an EMth$_{\mathrm{IMP\,s^{-1}}}$ of 10 and an EMth$_{\mathrm{dur}}$ of 3–5 s for the geophones with box. In contrast, a GVth of 0.005–0.03 mm s^{-1} and the same EMth parameters are proposed for the geophones directly fixed at bedrock.

7 Conclusions

Monitoring torrents prone to debris flows is an increasing activity all over the world. The efficiency of the geophones to monitor the occurrence of torrential processes has been widely proved, and so it is their convenience for warning purposes (LaHusen, 2005b; Suwa and Okuda, 1985; Bessason et al., 2007; Badoux et al., 2009; Huang et al., 2007; Arattano and Moia, 1999). However, there is a great variety of data recording systems, highly conditioned by the technical details of each monitoring station and many site specific factors that affect the ground vibration measured.

In this work, two different recording systems have been compared, both of them installed in the Rebaixader torrent (Central Pyrenees). The first data recording system consists of collecting the entire ground velocity signal (GVS), digitized at a high frequency rate (250 Hz), while the second one is a simplified system, which records a transformed signal (IS). Both recording systems demonstrated their efficiency on recording the typical debris-flow features including the different phases of the events. Thus, both techniques should be considered as suitable for debris-flow monitoring. On one hand, GVS recording technique provides more information about the signal generated by the debris-flow passing, but it generates a large amount of data and subsequently consumes more electric power and time of analysis. On the other hand, IS recording technique provides less information on the signal, but it has been demonstrated that it is reliable for detection. Moreover it requires less power and simplifies the data collecting and gathering. These latter issues make the transformed signal especially useful for a warning system.

The data analysis showed that the differences between debris flows and debris floods can be observed by both recording techniques (GVS and IS). The differences are mainly based on the shape of the signal and the values of the ground velocity. In both stations (FLOW-WR and FLOW-SPI), the results point out that the geophones that better show the debris-flow features are the ones installed closest to the active channel. It is also worthwhile that the active channel runs over bedrock on these cross-sections. The geophones located far from the active channel show less clearly the characteristics of debris flows. All these results suggest that the optimum position for a geophone to obtain reliable records of debris flows would be as closest as possible to the active channel, and preferably where it runs over bedrock.

The site-specific factors that influence the ground vibration measured at the geophones were evaluated by field tests and the comparison of the GVS registered at three geophones. Two major conclusions were obtained: (a) the distance produces a linear to exponential attenuation of the signal; and (b) the assembly of the geophone can strongly condition the amplification of the signal. This last conclusion was clearly observed by comparing one geophone directly fixed at bedrock with another one mounted in a metal sheet box, which is attached to the bedrock. The results suggest that the metal sheet box amplifies the signal. At Rebaixader, this amplification was useful for the detection of events, because the geophones with a metal box were not placed close to the active channel. However, other amplification system (like an electronic amplifier in the circuit board) would be more appropriate, because the exact amplification factor could be known and controlled.

Finally, the choice of a correct Detection Threshold (Dth) is fundamental, since it could produce the loss of an event or a great number of false alarms. In this study a sensibility analysis of the parameters of the Dth was carried out. The results point out that the number of seconds over the IMP s^{-1} threshold (10 or 20 IMP s^{-1}) decrease exponentially as the ground velocity threshold (GVth) increases. From the sensibility analysis of the parameters it was noted that linearly or exponentially he ground velocity threshold GVth is the most important of the three parameters of the Dth.

Although many uncertainties are still remaining and additional data must be gathered and analysed, the outcomes of this research improve the knowledge on the use of seismic sensors for the detection of debris flow and other torrential processes and help on the design of a warning system using geophones as key sensors.

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Table 1. Summary of main characteristics of the geophones analysed in this paper. IMP s^{-1} stands for "impulses per second" and GVS stands for "ground velocity signal".

Geophone (abbreviation)	Mounting	Station (data recording system)	Distance to active channel (planimetric distance in m)	Material at the cross section
Geophone 3 (Geo3)	Metal sheet box attached to bedrock	FLOW-WR (IMP s^{-1})	25	Colluvium and bedrock
Geophone 3b (Geo3b)	Bedrock	FLOW-WR (IMP s^{-1})	25	Colluvium and bedrock
Geophone 4 (Geo4)	Metal sheet box attached to bedrock	FLOW-WR (IMP s^{-1})	8	Bedrock
Geophone 5 (Geo5)	Bedrock	FLOW-SPI (GVS)	3	Bedrock
Geophone 6 (Geo6)	Buried into soil	FLOW-SPI (GVS)	3	Colluvium and bedrock
Geophone 7 (Geo7)	Buried into soil	FLOW-SPI (GVS)	5	Colluvium and bedrock

Table 2. : Characteristics of the events analysed in this work

Date	Type	Volume (m^3)
4 Jul 2012	Debris flow	16 200
11 Jul 2010	Debris flow	12 500
27 Jun 2012	Debris flow	4000
5 Aug 2011	Debris flood	2500
25 Mar 2010	Debris flow	2100
5 Jul 2012	Debris flood	1000
7 Jun 2012	Debris flood	750

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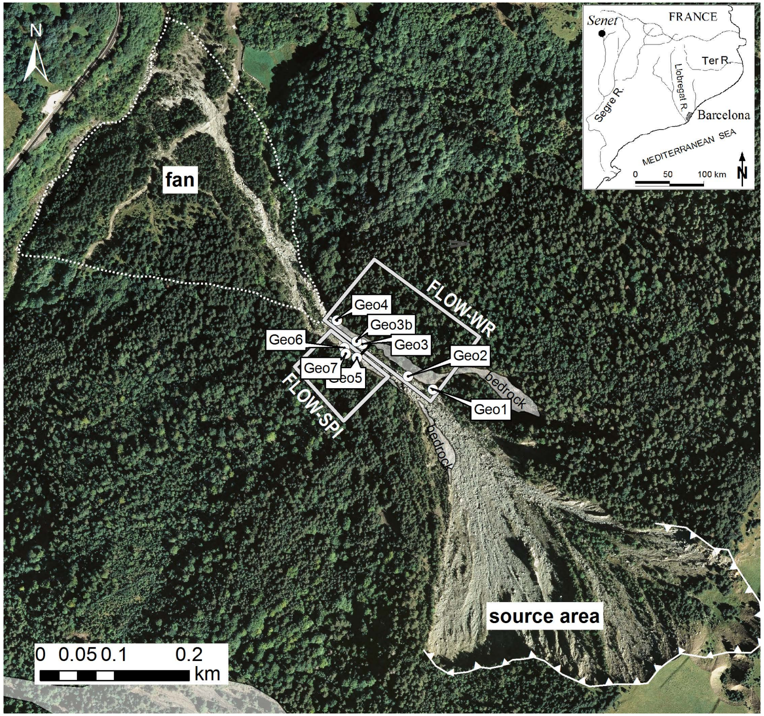

Fig. 1. The Rebaixader torrent, its fan and source area. Seismic stations (FLOW-WR and FLOW-SPI) and the corresponding geophones are indicated and labelled. The ultrasonic device is represented by a black line in the middle of the channel reach. Inset shows the location of the Rebaixader site.

Fig. 2. (a) Downstream view inside the channel indicating the places where the geophones are placed. Pictures of the detailed assemblies are shown in **(b)–(d)**.

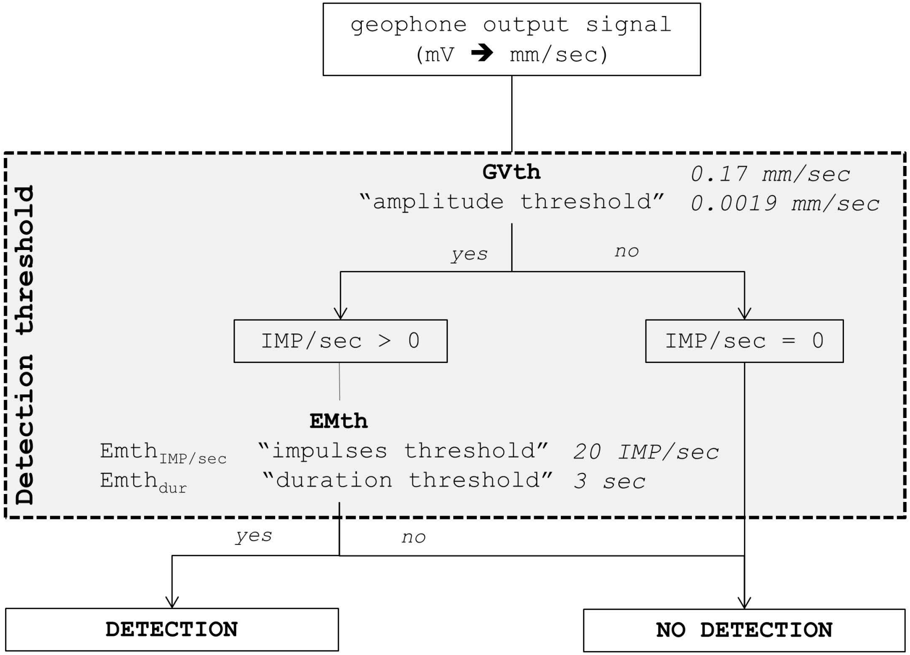

Fig. 3. Flow chart of the event detection of FLOW-WR system in the Rebaixader. In italics, the value of the parameters used nowadays in the Rebaixader.

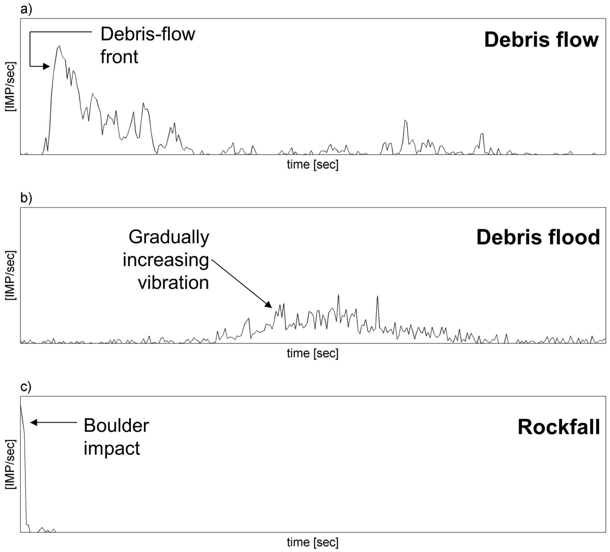

Fig. 4. Typical shapes of the IS signal registered during a debris flow **(a)** debris flood **(b)** and rockfall **(c)**. Horizontal and vertical scales are the same in the three cases.

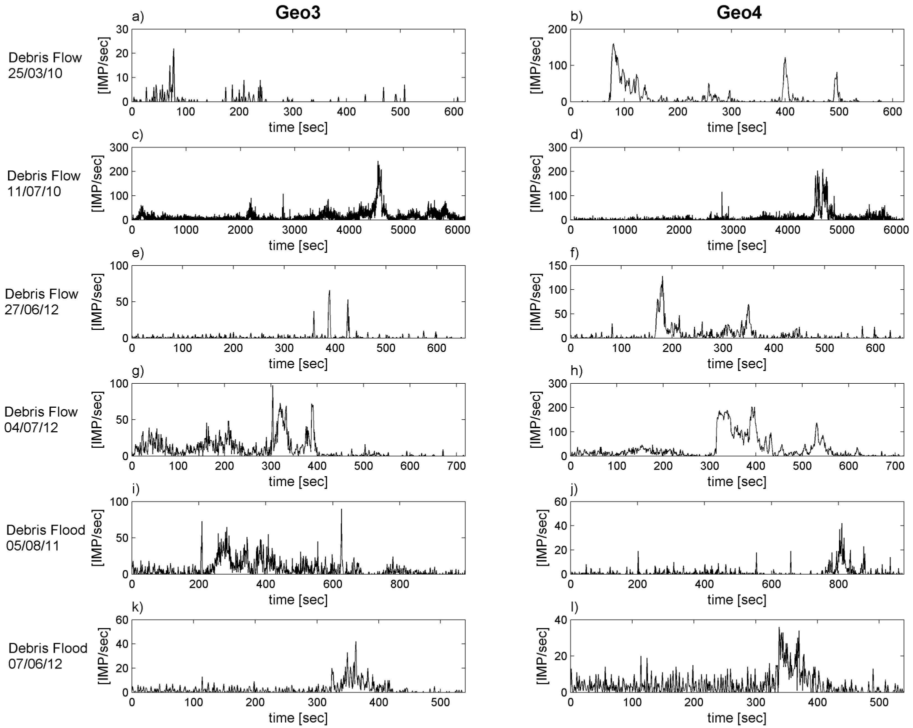

Fig. 5. Plots of the ground vibration (time vs. IMP s^{-1}) during some debris flows and debris floods occurred in the Rebaixader monitoring site. Left column (**a**, **c**, **e**, **g**, **i**, **k**) corresponds to Geo3 and the right column (**b**, **d**, **f**, **h**, **j**, **l**) to Geo4.

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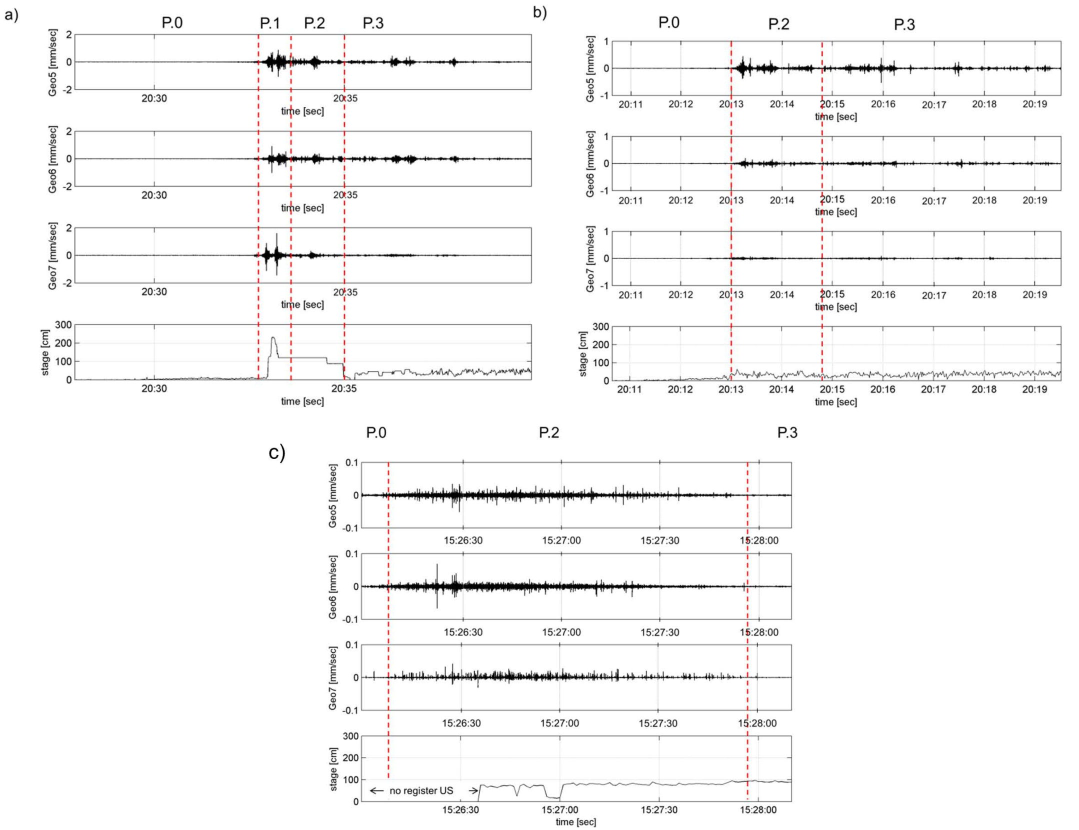

Fig. 6. Ground vibration signals recorded previously and during the debris flow occurred on the 4 July 2012 **(a)**, 27 June 2012 **(b)** and the debris flood occurred on the 5 July 2012 **(c)**. For all the events, data from Geo5, Geo6, Geo7 and US device are shown respectively.

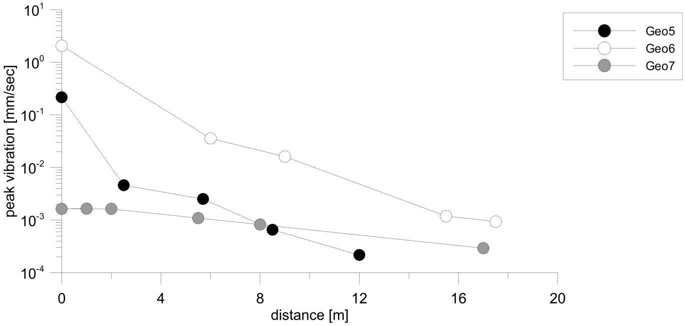

Fig. 7. Distance vs. peak of the ground vibration signals recorded during field tests. Geophones Geo6 and Geo7 are installed in colluvium and Geo5 is installed in bedrock.

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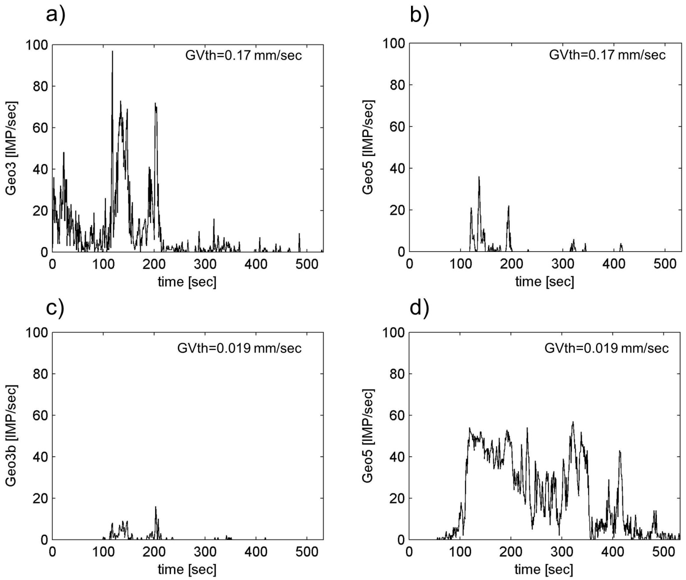

Fig. 8. Comparison of the IS signal observed during 4 July 2012 debris flow. Data registered at Geo3 **(a)** and Geo3b **(c)** and the signal obtained from the transformation of data from Geo5 into IS time series (**b** and **d**).

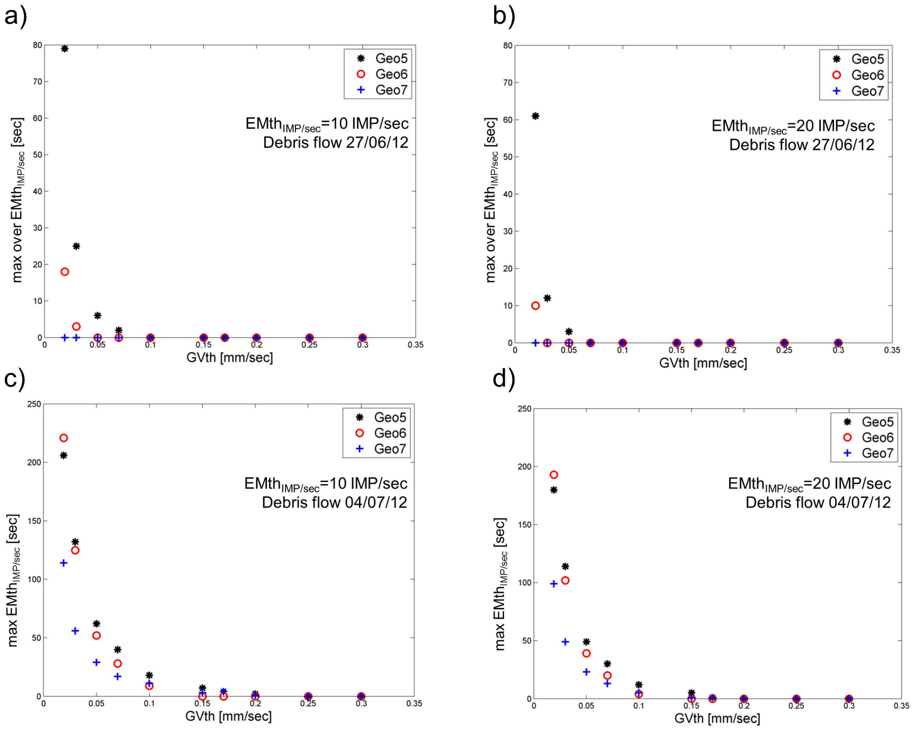

Fig. 9. Influence of the three parameters of the detection threshold (Dth): ground velocity threshold (GVth) vs. duration over the IMP s^{-1} threshold of the event mode ($\text{EMth}_{\text{IMP s}^{-1}}$). The value of the EMth is 10 IMP s^{-1} for (**a** and **c**) and 20 IMP s^{-1} for (**b** and **d**).