Velio Coviello

Debris flow seismic monitoring and warning

Ph.D. Degree in Geotechnical Engineering

POLITECNICO DI TORINO

Istituto di Ricerca per la Protezione Idrogeologica

Front cover: debris flow in the Gadria basin, courtesy of Bolzano Province (July 18, 2013).

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La scienza della natura è un bene che appartiene a tutti. Tutti vorrebbero conoscere il loro bene ma pochi hanno il tempo o la pazienza di calcolarlo. Newton lo ha calcolato per loro. Qui ci si dovrà accontentare del risultato di quei calcoli.

Voltaire, *Éléments de la philosophie de Newton*
mis à la portée de tout le monde, 1738

Acknowledgments

This adventure started with one year of work focused on high altitude rock wall monitoring in the framework of the Interreg Alcotra project MASSA. The aim of this research activity was the identification of climatic and seismic precursory patterns that may lead to a rock fall. The skills I acquired the first year in code developing and signal processing were very useful to face my new Ph.D. topic. Thanks to results and especially to the shortcomings of this experience, I was pushed to better focus my Ph.D. research activity. I wish to thank Marta Chiarle (CNR IRPI) for her support during this first, somehow difficult, period.

Research based on field monitoring data analysis are often risky because the results firstly depend on the success of the data collection phase. I am grateful to Gabriele Savio for his generous collaboration during the field work activities in the Marderello basin, Western Italian Alps, and to Pierpaolo Macconi (Provincia Autonoma di Bolzano) for his important support in the field work conducted in the Gadria basin, Eastern Italian Alps. I also want to warmly thank Clàudia Abancó and Marcel Hürlimann (UPC Barcelona) for having shared with me the precious monitoring data collected in the Rebaixader basin, Central Pyrenees (Spain). I experienced how difficult is to gather debris flow monitoring data, I really appreciated their willingness. Similarly, I wish to thank Brian McArdell (WSL), for putting at my disposal a dataset of seismic monitoring data collected in the Ilgraben catchment (Switzerland).

I am extremely grateful to Massimiliano Sanna, Stefano Perin and Marco Del Missier from the company SIAP+MICROS for their fundamental collaboration during the design, testing and installation of the multi-parametric recording unit developed during my Ph.D. and installed in the Gadria basin. Of course I cannot forget to thank all the Gadria research team, in particular Marco Cavalli, Lorenzo Marchi and Francesco Comiti. Without all the work they made during the last years, and without the support of the SedAlp project (Alpine Space Programme 2007-2013), “my geophones” data alone would have never allowed the achievement of the results hereinafter presented.

In 2014 I had the possibility to visit the U.S. Geolgical Survey (USGS), Colorado (USA). To work with the “Chalk Cliffs team” was a great opportunity to improve my knowledge on debris flow monitoring in steep catchments. I wish to thank Jeffrey Coe, Jason Kean and Joel Smith for their support and for the enriching discussion we had during the long trips to Chalk Cliffs.

Finally, I would express all my gratitude to Laura Turconi (CNR IRPI), who involved me in the research activities carried out in the Marderello basin and financed my last year of Ph.D., and to Massimo Arattano (CNR IRPI) for these intense and fruitful four years of common work.

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1 Introduction

1.1 Context

Landslide phenomena severely impact environment, infrastructures, and socio-economic activities, frequently resulting in fatalities (Petley, 2012). Catastrophic landslides can be activated by earthquakes (Keefer, 2002), climatic factors as rainfall (Guzzetti et al., 2007a) and temperature variations (Huggel, 2009) or a combination of both (Govi et al., 2002), but also by a variety of process related to human activities, like the failure of tailings dams (Rico et al., 2008). In recent years a possible correlation between slope instabilities and global warming was hypothesized: the climatic change perturbates natural processes, and in some cases can increase the frequency of instabilities, thus trigger important implications for hazard assessment and future development of mountain areas (Evans and Clague, 1994; Gruber and Haeberli, 2007; Huggel et al., 2012).

In the last three Centuries, the population of Europe has grown from about 120 millions to more than 750. In particular, the population of Italy has grown from 13 million of inhabitants in 1700 to more the 60 in 2004 (*Censimento* ISTAT, 2011). This population increase, coupled with an economic model based on the myth of growth that rarely consider any natural and physical limit, is associated with an intensive exploitation of lands. Thus, in the last decades, the rate of land consumption increased dramatically. In many areas of Italy, due to the local physiographical setting, expansion of new settlements and infrastructure occurred in highly dangerous or potentially hazardous areas, like alluvial fans. As a consequence, the joint effect of population growth and of the augmentation of built-up areas results in the increase of risk associated to landslides.

Floods and landslides kill people almost every year in Italy but fast-moving landslides, including rock falls, rockslides, rock avalanches, and debris flows, cause the largest number of deaths (Guzzetti et al., 2005). In particular, debris flow dangerousness and destructiveness is due to different factors: (i) their sediment transport and deposition capability, which may also reach large sizes (boulders of several cubic meters can be transported), (ii) their steep fronts, which may reach several meters of height and (iii) their high velocities. As an example, the events occurred in Campania on May 5, 1997 caused 162 fatalities and injured 70 people at 13 sites (Guzzetti et al., 2005). As already stated, the construction of residential buildings and transport infrastructures on debris flow fans has progressively increased the vulnerability to such events, thus augmenting the overall risk.

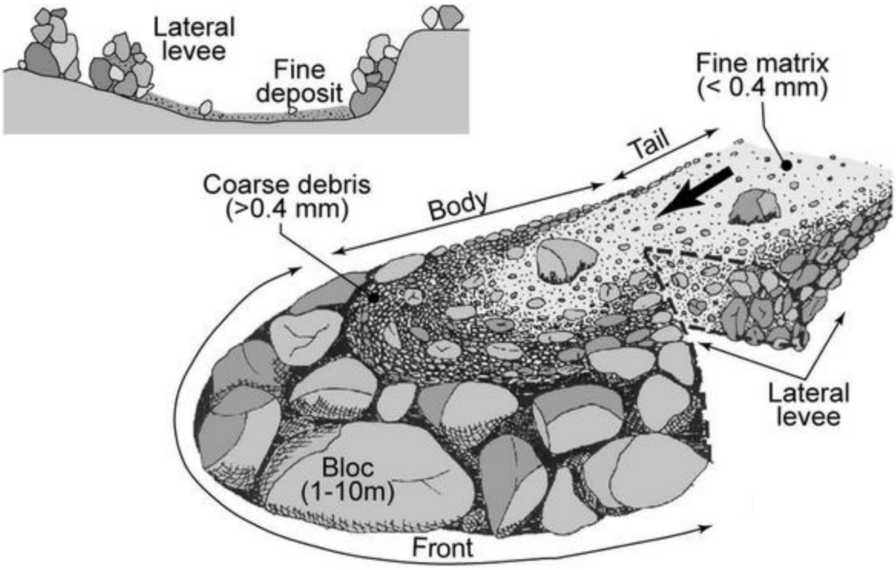

Figure 1 - Schematic representation of debris flow body and deposits (modified after Bardoux, 2002).

Debris flows consist in fast gravitational flows involving multi-phase mixtures where water-saturated debris ranges from boulders, mainly concentrated in the front, to grains (Figure 1). Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction. Both solid and fluid forces vitally influence the motion, distinguishing debris flows from related phenomena such as rock avalanches and sediment-laden water floods. Whereas solid grain forces dominate the physics of avalanches, and fluid forces dominate the physics of floods, solid and fluid forces must act in concert to produce a debris flow (Iverson, 1997). Conditions required for debris flow occurrence include the availability of relevant amounts of loose debris, high slopes and sudden water inflows that is normally produced by extreme rainfall but may also come from collapse of channel obstructions, rapid snow-melt or glacial lakes outburst floods.

The importance of monitoring in instrumented basins prone to debris flow is nowadays straightforward and universally recognized (Berti et al., 2000; Comiti et al., 2014; Hu et al., 2011; Hürlimann et al., 2003, 2013; Marchi et al., 2002; McCoy et al., 2013; Navratil et al., 2013; Suwa et al., 2009; Yin et al., 2011). Long-term instrumental observations of debris flows (e.g. Marchi et al., 2002; Suwa et al., 2011) can provide fundamental information to understand the behavior of these phenomena. The quantification of sediment volumes transported by debris flows, along with their temporal frequency and flow characteristics, is of crucial importance for land-use planning, the delineation of hazard zones (e.g. Tsai et al., 2011), and the designing of torrent control structures. Instrumented basins can also provide essential data for debris flow modeling (Arattano et al., 2006; Hutter et al., 1994), deriving local or regional rainfall thresholds for debris flow initiation (Coe et al., 2008; Guzzetti et al., 2007b), and designing active and passive countermeasures. Early warning systems (EWSs) are receiving a growing attention, given their lower cost in comparison with active countermeasures (Hungr et al., 1987).

EWSs are defined as the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss (UNEP, 2012). This definition encompasses the range of factors necessary to achieve effective responses to warnings; as a consequence EWSs have to address four key elements: (i) a comprehensive assessment of the risks; (ii) a sensor-based monitoring, analysis and forecasting of the hazards; (iii) a plan for the communication and the dissemination of alerts; (iv) local capabilities and strategies to respond to the warnings received. A weakness in any one of these aspects could results in the failure of the whole system (UNEP, 2012). Several studies investigate the reliability of landslide EWS, their comparability to alternative protection measures and their cost-effectiveness (Cloutier et al., 2014; Michoud et al., 2013; Sorensen, 2000; Stähli et al., 2014).

EWSs for debris flows can be classified into two main types: advance EWS and event EWS (Arattano and Marchi, 2008). Advance EWSs predict the possible occurrence of a debris flow by monitoring hydro-meteorological processes that may lead to initiation conditions, typically rainfall. This kind of EWS have been deployed since the 1970s in the USA (Keefer et al., 1987) and nowadays are widely adopted worldwide (Aleotti, 2004; Baum and Godt, 2009; Jakob et al., 2011). Even though their widespread adoption, these latter systems are prone to false alarms because they are heavily affected by the uncertainties in the precipitation forecasts and in the estimates of local threshold curves. Event EWSs are based on the detection of debris flows when the processes are in progress. They have a much smaller lead time than advance warning ones and their effectiveness strictly depends on the possibility (i) to perform accurate and rapid measurements; (ii) to automatically process, store and validate monitoring data; (iii) to promptly disseminate the obtained information spreading an alarm. An event EWS for debris flows is based on measures from wire sensors, ground vibration sensors or stage meters, upstream of a precisely defined vulnerable site. They would be particularly effective in the protection of all those vulnerable infrastructures (like railways and roads) that would not require too much alert time to give a warn and so defend their users. Owing to such characteristics, event EWSs are potentially highly reliable, even though the need of sensor redundancy and of regular maintenance increases the costs. But their designing is quite complex and needs a complete knowledge of the site dynamic and often a set of already available monitoring data. That’s why very few examples of event EWS have been till now deployed (e.g. Badoux et al., 2008).

1.2 Objectives of the study

The general objectives of this thesis are (i) to discuss the potentiality of seismic monitoring data for the understanding of the dynamics of torrential processes, in particular debris flow, and (ii) to present an integrated, event EWS based on ground vibration data, designed, installed and tested in the framework of my Ph.D. In the following, the specific objectives and the relative achievements of this thesis will be addressed.

1.2.1 Synthetic protocol for debris flow seismic monitoring

Standardization of measurement procedures and performances are important goals in every field of science and are in general intensely pursued by scientists. Certain natural phenomena, however, present particularly difficult challenges in this regard and many efforts are still needed to actually reach standardization and systematic performance of measurements. Debris flows certainly belong to this latter category. Due to their low frequency of occurrence, their short duration and their sudden and abrupt nature they are extremely difficult to be measured. Only instrumented basins where debris flows occur with a sufficiently high frequency per year allow systematic monitoring activities. Even though during the last decades several such basin have been instrumented, field measurement data are still scanty and methods of measurement are not yet sufficiently standardized. One of the goals of the European Territorial Cooperation project SedAlp “Sediment management in Alpine basins: integrating sediment continuum, risk mitigation and hydropower” (Alpine Space Programme 2007-2013) is to make some advancement in this direction. One of the expected outputs of the SedAlp project is a protocol on debris flow monitoring. **The first aim of this thesis is to contribute to develop such a protocol in regards to debris flow seismic monitoring**.

1.2.2 Processing the ground vibration signal produced by debris flows

Ground vibration sensors have been increasingly used and tested, during the last few years, as devices to monitor debris flows and they have also been proposed as one of the more reliable devices for the design of debris flow warning systems. The need to process the output of ground vibration sensors, to diminish the amount of data to be recorded, is usually due to the reduced storing capabilities and the limited power supply, normally provided by solar panels, available in the high mountain environment. There are different methods that can be found in literature to process the ground vibration signal produced by debris flows. In this paper we will discuss the two most commonly employed: the method of amplitude and the method of impulses. These two methods of data processing are analyzed describing their origin and their use, presenting examples of applications and their main advantages and shortcomings. The two methods are then applied to process the ground vibration raw data produced by a debris flow occurred in the Rebaixader Torrent (Spanish Pyrenees) in 2012. **The second purpose of this thesis is to provide means to decide how to design a debris flow monitoring system based on of ground vibration detectors and which data processing methods to use**.

1.2.3 Detecting torrential processes from a distancewith a seismic monitoring network

The detection of debris flows through seismic devices occurs at a certain distance from the channel bed. Ground vibration detectors are installed outside of the flow path, usually along the banks of the torrent or on the surrounding valley slopes, in order to avoid damage or even complete destruction. Seismic networks, however, are also prone to detect other earth surface processes that can be confused with the passage of a debris flow. Recognizing these other processes is important, particularly when the seismic network is used for warning purposes and not only for monitoring. To this aim, two seismic networks were installed in two instrumented basins located in the Italian Alps. Both networks were designed for debris flow monitoring purposes and for testing warning algorithms. The seismic recordings of torrential processes that occurred at different distance from the monitoring networks, within and outside the monitored channels, are presented and discussed. It was found that knowledge of the waveform that these different processes produce is critical to the successful design and implementation of seismic networks for debris flow warning. **The third aim of this thesis is to present and to discuss the seismic recordings produced by different torrential processes that occurred in two basins prone to debris flow**.

1.2.4 Methods for debris flow seismic warning

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. To this aim, the methods of amplitude and impulses have been also applied to some seismic recordings obtained in the instrumented basin of Illgraben (Switzerland) and Chalk Cliffs (USA). **The fourth objective of this work is to investigate the impact of the data processing on the efficacy of the algorithms employed for warning.**

1.2.5 Algorithm for debris flows early warnings system based on seismic monitoring data

The final goal of this thesis is to propose an effective warning algorithm from debris flow based on real time seismic monitoring data. Data from two years of seismic monitoring performed in the Gadria basin (Northeaster Alps) are presented and discussed, together with the warning algorithm integrated in the system since 2014. In summer 2014 the alarm was correctly triggered by a debris flow and a red light was activated 3 minutes before the passage of the main front through the cross-section where this experimental semaphore is installed. The alarm lasted for the whole duration of the flow, correctly switching off after 20 minutes. Testing the algorithm on the whole seismic dataset recorded during both summers 2013 and 2014, the two debris flows event occurred in this time interval were correctly detected and only 3 false alarm where produced. After numerical simulation, it was possible to state that to eliminate false alarms a non-simultaneousness criterion in the threshold triggering can be adopted. The analysis of the frequency content of the seismic traces recorded at Gadria also allowed to draw some preliminary conclusions on the spectral characterization of the debris flow phenomena through geophone data. Some future developments are also outlined: the next step in the definition of a more advanced and robust warning system would be possible integrating the spectral information in the warning algorithm.

1.3 Thesis development and outline

This Ph.D. thesis can be considered the synthesis of 4 years of work I made in the field of landslide seismic monitoring. Most part of the work presented in the thesis was conducted at the Research Institute for Geo-Hydrological Protection (Instituto di Ricerca per la Protezione Idrogeologica, IRPI) of the Italian National Research Council (Consiglio Nazionale delle Ricerche, CNR), in the framework of National and European projects. The field work had a fundamental role in the story of my thesis. Research activities focused on field monitoring data analysis are often risky because the results clearly depend on the success of the data collection phase. Moreover, once data have been collected with great efforts, further time and energy is needed to interpret them. Inevitably, the work therein presented is to some extent the result of a team work. In particular, both in Marderello and Gadria catchments my work was mainly focused on the design, installation, and maintenance of the seismic monitoring equipment and on the analysis of the data collected. Without other monitoring data that were put at my disposal, my work would have been significantly limited. However, in this thesis I present what can be consider the outcome of my work.

During my Ph.D. I had the possibility to visit the U.S. Geolgical Survey (USGS), Colorado (USA). To work within the Landslides Hazards Program, in particular in the instrumented site of Chalk Cliffs, was a great opportunity to gather new data and to further test the methods and the procedures I developed during two field work seasons in the Italian Alps.

In the traditional structure of a Ph.D. thesis, after a general introduction, the explanation of the methods follows the description of the study sites. This is followed by the analysis of the collected data (results), by their discussion and finally by the conclusions. However, another strategy can be adopted, based on quasi-independent chapters that often have already been or are going to be transformed in papers. I have chosen this latter way, also because of the pressure to publish I am exposed to like every early career researcher is nowadays. As a consequence, this thesis is structured in chapters where methods and results are respectively presented and discussed. Each chapter could be read independently but they are logically sorted: because of that, I would recommend to read them progressively. In the following, I provide the most relevant references of the papers I contributed to write.

After this general Introduction (Chapter 1), the Chapter 2 explores the topic of debris flow detection by means of seismic sensors, an open issue in the frame of the standardization of debris flow monitoring. Part of the content of this chapter was published in the volume 3 of the proceedings Engineering Geology for Society and Territory (Arattano et al., 2015b), another part included in a paper submitted to the journal Natural Hazards (Coviello et al., 2015a). In Chapter 3 the two main processing methods of the ground vibration signal produced by debris flows are discussed, presenting the application of both methods to the geophone raw data of a debris flow occurred in the Rebaixader Torrent (Spanish Pyrenees) on July 4, 2012. Part of the results presented in this chapter were published in the journal Computers & Geosciences (Arattano et al., 2014). The Chapter 4 presents the seismic recordings produced by torrential processes, other than debris flows, occurred along two monitored torrents located in the Italia Alps: the Marderello and the Gadria. The analysis of these data is of particular interest in case of using seismic networks for the designing of warning systems. Most part of the content of this chapter has been included in the paper submitted to the journal Natural Hazards (Coviello et al., 2015a). The general settings of the Marderello monitoring station have been already published in the volume 3 of the proceedings Engineering Geology for Society and Territory (Turconi et al., 2015). In Chapter 5, the impact of the two main methods of data processing on the efficacy of the algorithms employed for debris flows seismic warning is investigated. Part of the content of this chapter was included in the paper submitted to the International Journal of Erosion Control Engineering (Arattano et al., 2015c), part has been presented to the General Assembly of the European Geosciences Union (Coviello et al., 2015c). Chapter 6 presents the warning algorithm for debris flow based on seismic monitoring data, applied and tested in the Gadria and the Marderello basins. In particular, the Gadria testing field for debris flow early warning system was presented in the article published in Natural Hazards and Earth System Science Discussion (Arattano et al., 2015d) while the results of the application of the algorithm presented in this chapter will be submitted to the journal Landslides (Coviello et al., in preparation).

2 Methods and procedures for debris flow seismic monitoring

2.1 Introduction

Monitoring of debris flows in instrumented catchments allows the collection of field data that provide an important comparison with the geomorphologic and topographical surveys of erosion, sediment supply and channel evolution. The collected data are also very important for rheological studies (Arattano et al., 2006) and the mathematical modeling of debris flows (Arattano and Franzi, 2004; Lin et al., 2005; Tsai et al., 2011), as well as for hazard assessment, land-use planning, design of torrent control structures and warning systems. In fact, as an example, calculations of the potential debris flow discharge that is only based on observation of historical events could be deceptive (Mavrouli et al., 2014).

Japan and China have pioneered the researches on debris flow monitoring (Suwa and Okuda, 1985; Zhang, 1993) and long time series of data have been recorded in these countries and are available today to the researchers working in this field (Hu et al., 2011; Suwa et al., 2011). In Taiwan, several sites were also equipped for monitoring debris flows, mainly for warning purposes (Yin et al., 2011). In the United States early experiences on instrumental observations of debris flows were carried out by Pierson (1986) in some channels on the flanks of Mount St. Helens. More recently, a monitoring equipment was installed at Chalk Cliffs, a debris-flow prone catchment on the Colorado Rocky Mountains (Coe et al., 2008; McCoy et al., 2010). In Europe, one of the first catchments specifically instrumented for debris-flow monitoring was probably the Moscardo Torrent in the Eastern Italian Alps (Marchi et al., 2002). Further sites were then instrumented in Italy in the late 1990s and early 2000s (Tecca et al., 2003) and in Switzerland (Berger et al., 2011; Hürlimann et al., 2003; McArdell et al., 2007). More recently some new sites have been instrumented in Austria (Kogelnig et al., 2011), France (Navratil et al., 2013), Spain (Hürlimann et al., 2013) and Italy (Comiti et al., 2014). However, the number of monitoring sites and the amount of recorded data on debris flows remains still limited if compared to the existing sites where landslides and fluvial sediment transport are subject to monitoring, just to mention two similar research sectors.

The limited number of debris monitoring sites worldwide and the great difficulties in collecting enough field data of such a low-frequency phenomenon, which may sometimes occur just once a year in some of these sites, have certainly slowed down the researches and prevented the standardization of the methods, devices, techniques and procedures for debris-flow monitoring and data collection.

In 2012, an European Territorial Cooperation project named “Sediment management in Alpine basins: integrating sediment continuum, risk mitigation and hydropower” (SedAlp) has started in the frame of the Alpine Space Programme. The SedAlp project focuses on the integrated management of sediment transport in Alpine basins and one of its objective is to provide advancements towards the standardization of methods and data collection on sediment transport. One of its expected outputs is a protocol to standardize the data collection methods in debris-flow monitoring. The protocol will aim at describing the minimum requirements for a debris-flow monitoring site and at illustrating the existing sensors and methods of measurements and data collection.

In the following we will explore the debris flow detection by means of seismic sensors, an open issue in the frame of the standardization of debris flow monitoring.

2.2 Debris flow seismic detection

Seismic monitoring has been profusely employed worldwide to detect the ground vibrations induced by slope deformation and/or landslide detachment and propagation. As an example, the analysis of seismic signals has been carried out to investigate of the existence of precursory patterns leading to collapse and rockfalls (Amitrano et al., 2005; Levy et al., 2011). The correlation between climatic conditions and microseismic activity may also provide relevant information on the dynamics of unstable slopes (Coviello et al., 2015b; Occhiena et al., 2012).

During the last decades, the monitoring of debris flows through ground vibration detectors (GVDs) has been carried out more and more frequently. Their output is a voltage that is directly proportional to the ground vibration velocity (Figure 2). The latter can be derived from the voltage through a transduction constant, provided by the company that produces the device (Figure 3). Actually, GVD present the advantage to be deployable at a distance from the channel bed and for this reason they offer a greater flexibility than other type of sensors (e.g. radar, laser and ultrasonic sensors) and can be more easily adapted to the different and often difficult conditions that are found in the field (Table 1). The monitoring of ground vibrations induced by debris flows allows velocity measurements, both through the identification of characteristic features in the signal or through the techniques of cross-correlation. The latter is defined as the correlation of a series of data with another related series, shifted by a particular time lag. Cross-correlation allows to calculate the value of this time lag with an objective methodology (Arattano and Marchi, 2005).

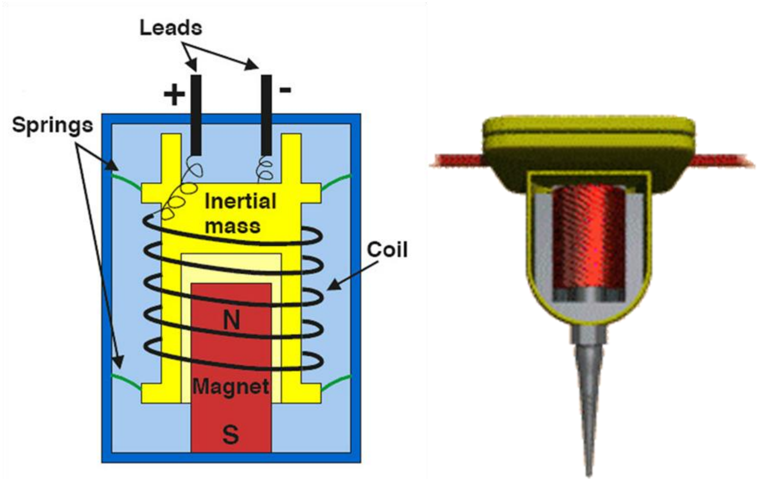

Figure 2 - Outline of the working principles of ground vibration detectors (left) and sketch of a mono-dimensional, vertical geophone (right).

The monitoring results obtained through seismic sensors could also be used to estimate the flow stage variations with time. This would require previous calibration, but would lead to determine the debris flow hydrograph and would therefore, subsequently allow an estimation of the debris-flow volume (Arattano et al., 2015a; Navratil et al., 2013). Actually great efforts are still needed to reach reliable estimations of volumes through the use of monitoring devices, such as radar, ultrasonic or ground vibration sensors. The methodologies commonly employed, in fact, make use of constant values for the velocity of the debris flow in the calculations, although the surface velocity is known to vary up to 50% during each single surge (Arattano and Grattoni, 2000; Navratil et al., 2013; Suwa et al., 2009). However the possibility to collect more volume and velocity estimations obtained with different types of sensors, including the GVD, should greatly help to reach more reliable results.

Finally, since the GVD can detect the debris flow arrival some tens of seconds before its passage through the cross-section where the sensor is installed, they appear to be particularly promising for the development of warning systems against this destructive phenomenon. However there are many aspects of the seismic monitoring of debris flows that would still need standardization to obtain homogeneous and comparable measurements throughout the world and to produce a common data set of field observations. Therefore the draft of a protocol defining the requirements for a systematic ground vibration data collection would certainly be of great help.

Several devices have been employed and tested so far to detect the ground vibrations induced by debris flows: seismometers, geophones, accelerometers, hydro-phones, underground microphones, etc. (Itakura et al., 2005). Recently geophones, particularly mono-axial (1-D), vertical geophones, have become the most commonly used devices, for they robustness, low power consumption and relatively low cost. However a protocol discussing advantages and shortcomings of the different types of GVDs, describing the procedures for data collection, would be of utmost importance for better orientating the research on debris flow monitoring.

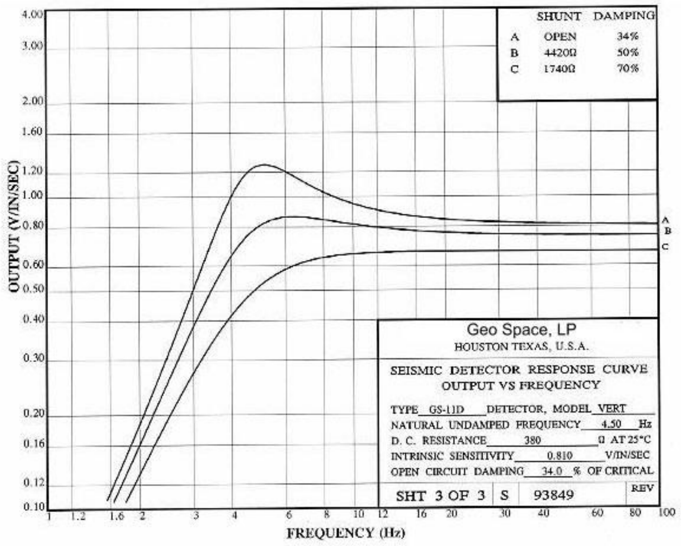

Figure 3 – Frequency response curves in V/in/s of a 4.5-Hz geophone.

2.2.1 Choice of the seismic sensor

Once the choice of GVDs to monitor debris flows has been made, many issues still remain to be solved. In general, the choice of the proper GVD to use for monitoring firstly relies on the frequency range under investigation. According to Lahusen (1996) the typical peak frequencies of a debris flow range between 30 and 80 Hz. Huang et al (2007) observed that at the surge front peak frequencies range between 10–30 Hz while they range between 60–80 Hz at the flow tail. The spectral analysis of seismic monitoring data gathered in the Rebaixader catchment, showed that the main frequency content of debris flows ranges between 10 and 60 Hz (Arattano et al., 2014). GVDs have different natural frequencies, providing a flat response proportional to ground velocity only above this frequency and a response falling at 12 dB/octave below (Figure 3). Consequently, GVDs with a maximum natural frequency of 10 Hz are suitable for debris flow monitoring, since they provide a flat response in the typical frequency range of these phenomena. However, further collection of field data might help in giving more precise indications on the best sensor to use. Recording equipment designed for debris flow monitoring should therefore provide continuous measurements of the different frequencies observable during the occurrence of the different phases of a debris flow. Only such a systematic collection of information might allow to make a sound choice of which type of geophone to employ.

Table 1 - Characteristics and performance parameters of most employed monitoring devices for debris flow monitoring and warning. Costs are in order of size and the complexity parameter includes the complete equipment installation, maintenance, data collection and processing.

	Active/passive	**Cost (€)**	**Complexity (1-5 scale)**	**Maximum detection distance**
1-D geophone	Passive	100	3	Hundreds of meters
Broadband seismic sensor	Passive	10000	5	Few kilometers
Stage sensor	Active	1000	1	In-channel
Video camera	Active	1000	2	Few meters
Load cell for force plate	Active	1000	4	In-channel

Similarly to the choice of the GVD with the proper natural frequency, also the definition of the sampling rate has to be done considering the main frequencies of the phenomenon under investigation. In fact, the voltage output that comes from a GVD is an analogical signal that is digitalized and then recorded. The sampling frequency or sampling rate of a signal f_S is the number of samples obtained in one second (samples per second), thus if Δt is the sampling interval:

$$f_s = \frac{1}{\Delta t} \tag{1}$$

The Nyquist-Shannon sampling criterion for a given signal or family of signals defines the Nyquist sampling rate $f_N$as twice the maximum component frequency f of the function being sampled (2):

$$f_N = 2f \tag{2}$$

from which, in order to obtain a correct digitalization of the raw signal:

$$f_s \geq f_N \tag{3}$$

Considering the frequency ranges mentioned before, applying the Nyquist–Shannon sampling theorem a sampling rate of at least 100 Hz would be required to accurately interpret the seismic signal produced by debris flows.

2.2.2 Distance from the channel bed

GVDs are commonly installed on the banks of the torrent at a distance from the channel that can be larger or smaller according to site channel and flow characteristics. The intensity of the ground vibrations that debris flows and mud flows produce diminishes with the distance, as the vibrations propagate from the torrent bed. Moreover, flows containing in sediment mixtures with smaller particles than debris flows (i.e. mud flows) may produce ground vibrations of lower intensities (Turconi et al., 2015). Recent observations made at Chalk Cliffs (Colorado, USA) showed how also the channel bed sediment contributes to damp the seismic signal (Kean et al., 2014). As a consequence, the optimal distances at which GVDs can be placed from the torrent to efficiently detect the passage of such an event is necessarily site-dependent and need specific investigations. However, some general guidelines based on instrument type and field condition can be given about the maximum practical distance from the channel bed at which installing GVDs. This distance mainly depends from (i) the characteristics of the employed GVDs (i.e. the working frequency range), (ii) the objective of the monitoring and (iii) the dimension of the network.

Geophones are low cost and easy to install GVDs, highly adaptable to different field conditions. However, they are significantly less sensitive to low frequencies (< 1 Hz) than seismometers. Using broadband seismic networks, the detection of large debris flows and intense bed load transport events is possible from a distance of kilometers (Burtin et al., 2009). Recently, monitoring data gathered with broadband seismometers in the Illgraben basin showed how approaching flows can be detected before they reach the in-channel location nearest the station, giving rise to a progressive increase of registered seismic energy (Burtin et al., 2014). Seismometers are a powerful tool that can be used to characterize torrential processes from a great distance. However, the cost of a complete seismic station is significantly higher than that of a geophone network, as well as the complexity of monitoring equipment installation, maintenance, and data analysis (Table 1).

As a consequence, when the evolution and the propagation of the debris flow along a specific reach of the torrent is the objective of the monitoring, geophones certainly are the optimal employable GVDs. Geophones guarantee an effective detection of in-channel flows from a maximum distance of some tens of meters. Moreover, topographical discontinuities can produce ground vibrations strong enough to be recorded by geophones placed at a distance of several hundred of meters (Arattano, 2003; Coviello et al., 2015a). Considering the distance from the channel bed at which they are installed, a correct choice of the amplification value to apply during the conversion of the analogical seismic signal in digital form has to be done to deal with amplitude attenuation. However, the proper distance from the channel bed at which installing the GVDs also depends from the dimension of the network. A distance sensor-channel significantly smaller than the distance from two GVD stations is recommended to avoid waveforms overlapping.

2.2.3 Methods of installation

The distance from the channel bed is not the only factor to take into account for estimating the GVD amplitude response. The method of installation of the geophones (Figure 4) would also require some sort of standardization, since it may lead to very different responses (Abancó et al., 2012).

Figure 4 - Different methods of installation of the geophones: (a) embedded in a concrete manhole, picture taken in the Gadria basin (Northeastern Alps, Italy); (b) fixed on rock, Chalk Cliff monitoring station (Colorado, USA); (c) directly dug in the ground, Marderello catchment (Northwester Alps, Italy).

The different methods of installation directly influence the voltage output of GVDs. In fact the type of installation (fixed on rocks, dug in the terrain, installed within a metal box, embedded in the wing of a check dam, etc.), can strongly affect the amplification of the output signal and thus require different levels of electronic amplification in the circuit boards of the recording unit employed for the monitoring. In the Gadria basin, a test we conducted in 2013 gave a first clear insight on the effect of the installation methods on the recorded signal. We tested two of a kind geophones, both placed in correspondence of the same cross section and at the same distance from the torrent but one mounted on the check-dam concrete (Geophone check-dam) and the other one directly installed in the ground (Geophone ground). Data gathered from a debris flow event that occurred in 2013 showed how the amplitude signal recorded by the geophone mounted on the check-dam concrete was significantly damped compared to the one installed in the ground (Figure 5). Indeed, the signal recorded by this latter sensor was affected by saturation and the magnitude of the different surges are not recognizable in the signal. This problem could be tackled designing a recording equipment that gave the possibility to set different amplification values for each geophone, according to its different type of installation on the ground.

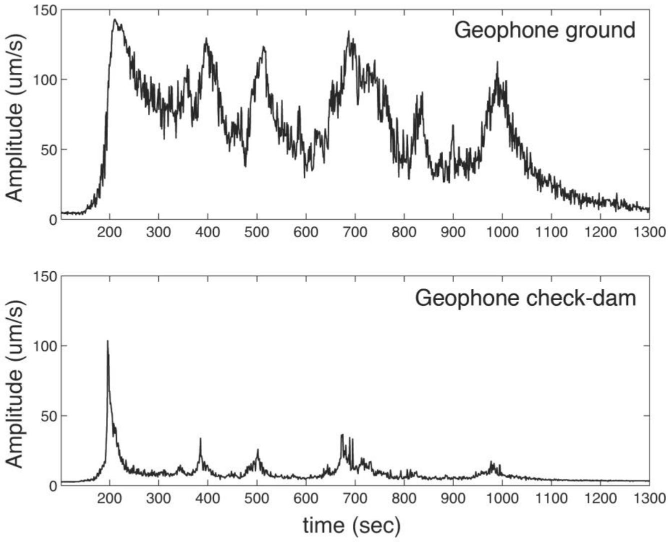

Figure 5 - Amplitude recorded by a couple of geophones placed at the same distance from the cannel, one directly installed in the ground (Geophone ground) and the other mounted on the check-dam concrete (Geophone check-dam).

2.2.4 Data processing

Another issue is the choice of the method to process the ground vibration signal. At the moment there are at least two main methods that are employed for the transformation of the raw seismic signal: the transformation into amplitude (Arattano, 1999) and the transformation into impulses (Abancó et al., 2012). The differences between the information that these two methods provide have been recently adequately investigated and clarified by Arattano et al. (2014). This is not a secondary issue, because the limited availability of field data in literature and the great difficulties in obtaining new data from the field require an extreme effort to valorize and exploit the already available data sets. Some of these latter consist of data processed with the transformation of the signal into Impulses and some other with the transformation into Amplitude. The best way to exploit at most the data recorded so far is probably to use both transformation methods in every existing and future installation, to contribute to increase the available data sets. This topic will be profusely addressed in the next chapter of this thesis.

2.3 Towards standardized monitoring methods

Addressing all the mentioned issues would thus require the design of a standardized recording unit that could provide different types of pre-scribed performances: as an example, the possibility to change the level of amplification of the signal via software and to assign different amplifications to each sensor. As previously mentioned this would allow, in fact, adapting the recording unit to the different field conditions and methods of installation of the sensors in the field. The unit should also perform both the transformation methods of the signal that have been employed so far in literature, that is the transformation into impulses and the transformation into amplitude. This would in fact permit to enrich the datasets already available, increasing the chances to improve the knowledge of the phenomenon. The transformation of the signal is also needed to reduce the amount of data to be recorded, to limit the problems of storage capacity and power consumption. The unit, in fact, should be powered by solar panels in order to be installable stand alone in every kind of field conditions where the power supply is inevitably limited.

The unit should also provide continuous measurements of the different frequencies observable during the occurrence of the different phases of a debris flow. This would eventually allow a sound choice of the natural frequency of the geophones to employ. Finally the recording unit should offer the chance to record the raw signal produced by the debris flow during its occurrence. The raw signal, in fact, might provide much more information than the transformed signal. This re-cording could be performed with a triggering threshold implemented in the unit. This possibility could also provide information for the development of warning algorithms. The fulfillment of all the mentioned requirements should favor a standardization of the field data collection worldwide. In the SedAlp project the attempt will be carried out to design such a standardized recording unit and to provide a first data set recorded with it. Different types of sensor installation will also be tested, identifying and so providing the level of amplification that each of them require to properly work.

3 Processing the ground vibration signal produced by debris flows

3.1 Introduction

Debris flows generally appear as waves of highly concentrated dispersions of poorly sorted sediment in water that display very steep fronts, which consist mostly of boulders. Behind the bouldery front the number of blocks gradually decreases and the surge becomes charged with pebble-sized fragments and then more and more diluted until it appears only as muddy water (Johnson, 1970; Takahashi, 2014). Debris floods are phenomena of massive bedload transport, that can also be described as very rapid surging flows of water in a steep channel, heavily charged with debris (Abancó et al., 2014; Hungr et al., 2013). A debris flood may transport quantities of sediment comparable to a debris flow, in the form of massive surges. However, the transport is due to tractive forces of the water that overlies the sediments. Therefore the peak discharge of a debris flood is more similar to a water flood, while debris flow discharges may be tens of times larger than major water floods (Hungr et al., 2013; VanDine, 1985).

Different types of devices that can be used to monitor these flow processes, but ground vibration detectors (GVD) present several advantages. It is very well known that strong ground vibrations are induced in the ground by the propagation of a debris flow. These vibrations can be conveniently detected by GVD placed in the surroundings of the torrent, usually along the banks. The installation of an array of GVD at a proper distance from the torrent bed may allow the estimation of important parameters such as the velocity of the main front and the mean velocity of the entire debris flow wave. A network of GVD may also detect the presence of subsequent surges behind the main front and, given the proportionality between the intensity of ground vibration and the flow height, it may also give, after a calibration, information on the evolution of flow height with time and even on the magnitude of the event.

When the debris flow reaches the sensor network and passes through the cross section where a GVD is placed, it produces a significant increase of the signal detected by the sensor itself. Usually this increase is way above the environmental noise that is present before the debris flow occurrence and this helps to clearly recognize the phenomenon. This has promoted some research efforts worldwide to use ground vibration sensors as tools to detect the occurrence of debris flows (Bessason et al., 2007; Chou et al., 2010; Cui et al., 2005; Fang et al., 2011; Huang et al., 2007; Kogelnig et al., 2011; Lahusen, 1998; Navratil et al., 2013; Suwa et al., 2000) and so to provide information useful for both theoretical ends (Arattano and Franzi, 2004), and practical purposes, such as the identification of warning algorithms.

Actually, before the arrival of the debris flow at the sensor site, a gradual increase of the signal can be usually observed. This rise starts in advance, several tens of seconds before the passage of the debris flow through the cross section where the sensor is installed. Therefore a GVD may also be used to detect the occurrence of a debris flow tens of seconds earlier than other type of devices, such as radars, ultrasonic sensors, trip wires, pendulums etc. that start their recording only when the debris flow has reached their position. This earlier detection might be very precious if the detectors, because of some specific field condition, had to be forcedly placed very close to the infrastructure to protect, for instance a road where the traffic had to be stopped through the activation of a cross light. In this latter case, in fact, stage or contact sensors could not grant enough time to activate the alarm. The presence of a high check dam or a natural fall upstream from the sensor position might even allow the detection of the arrival of the debris flows some hundreds of second before, since the fall of the debris flow from them could be detected by the ground vibration sensors (Arattano, 2003). These specific capabilities of GVD have more and more encouraged the investigation of their potentialities as possible debris flow warning tools and has also stimulated the research of warning algorithms based on the detection of ground vibration (Abancó et al., 2014; Arattano and Marchi, 2008; Badoux et al., 2008).

The most employed GVD so far to monitor debris flows include geophones, seismometers, accelerometers, underground microphones, hydrophones (Itakura et al., 2005). Among these latter sensors, however, given their relatively cheap cost and robustness, geophones have become those most commonly employed. The output voltage that comes from the geophone is an analogical signal that is usually digitalized at a convenient frequency rate before it is recorded in a data-logger. Moreover, after having been digitalized, the signal is often also conveniently processed to reduce the amount of data that has to be stored in the data-logger. In fact, in high mountain environment where debris flows monitoring devices are usually installed, power supply is generally provided only by solar panels and there are reduced storing capabilities.

Reaching a proper and effective use of the output signal of a GVD for both monitoring and warning purposes, however, still requires some research efforts. Many research issues, in fact, still need to be addressed, such as the method of installation of the geophones on the ground or the more proper level of amplification of the signal to adopt (Abancó et al., 2014; Arattano et al., 2015b). Among the different issues that still need to be solved there is certainly the more convenient way to process the voltage signal that represents the output of a GVD. This specific issue will be addressed in the following, after the presentation of the two main processing methods of the ground vibration signal produced by debris flows. Both methods will be then applied to the geophone raw data of a debris flow occurred in the Rebaixader Torrent (Spanish Pyrenees) on July 4, 2012.

3.2 Methods and data

3.2.1 The need of processing the geophone raw data

In Figure 6 the typical output of a geophone placed along a torrent bank is shown that is produced by the occurrence of a debris flow in the torrent. This signal is in analogical form and was recorded through the use of a magnetic tape (Arattano, 1999). Nowadays magnetic tapes are no more used and the recording occurs only in digital form.

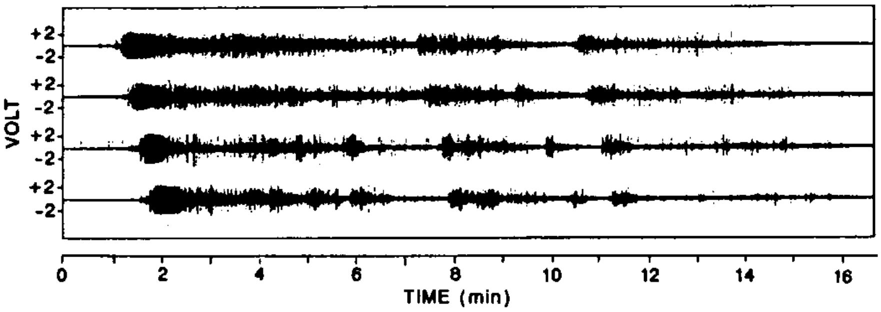

Figure 6 - Output of four seismic detectors placed at a distance of 100 m from each other along the right bank of a torrent reach of the Moscardo Torrent for a debris flow occurred on June 22, 1996 (modified after Arattano, 1999).

The frequencies of a signal produced by a debris flow usually range from 10 to 80-100 Hz (Abancó et al., 2014; Huang et al., 2007; Lahusen, 1998). Applying the Nyquist rule to obtain a data set representative of the original signal, a sampling frequency of at least 160-200 Hz would be required. To reduce the large amount of data derived from those high sampling rates, the processing of the digitalized signal becomes essential.

At least two different methods have been proposed for this purpose that can be found in literature: the method based on the counting of impulses (which will be called “method of Impulses” in the following) and the method of calculation of the amplitude of the signal (which will be called “method of Amplitude” in the following).

The latter has been proposed and for the first time used in the Moscardo Torrent (Arattano, 1999) while the first method is adopted in some Swiss torrents (Hürlimann et al., 2003) and more recently in the Spanish Pyrenees (Hürlimann et al., 2013). Both methods allow reducing the recording frequency rate to 1 Hz.

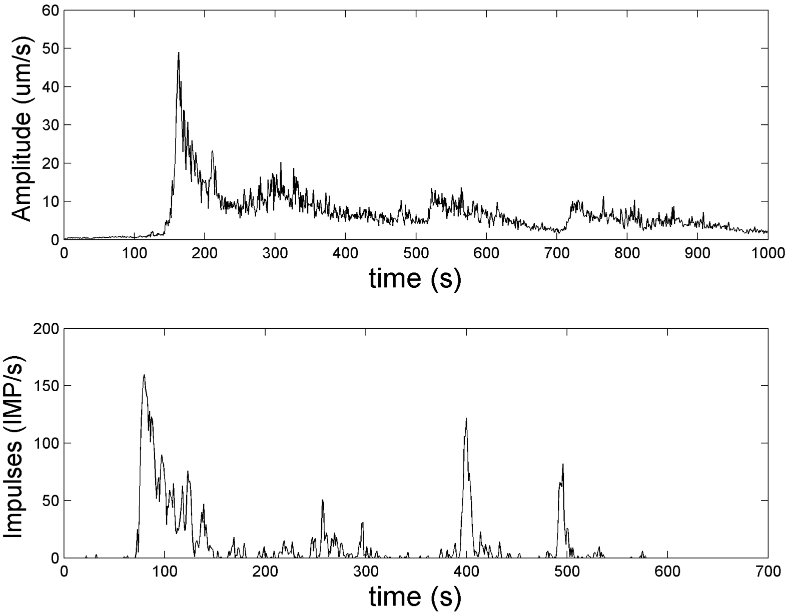

Figure 7 - The processing of the ground vibration voltage signal coming out from a geophone allows to more easily identify the main features of the debris flow such as its main front, the subsequent surges and the wave form. Above, a debris flow waveform revealed through the method of amplitude (Moscardo Torrent, Italy). Below, some debris flow waveforms revealed through the method of impulses (Rebaixader Torrent, Spain).

Apart from the need of reduction of the amount of data to be recorded, the processing of the voltage data obtained through the geophone is also carried out to better and more easily interpret them. In fact the geophone output is too complex to be analyzed in its raw form (Figure 6). Even when magnetic tapes were still in use and the signal was not digitalized, the raw signal was processed anyhow to analyze and interpret the geophone signal. In fact the processing of the signal allows to more easily identify the main features of the phenomenon, such as its main front, the subsequent surges, the wave form and so on (Figure 7).

The revelation of these features through the processing of the geophone raw data allows the measurements of several parameters, such as the velocity of the main front and of the subsequent surges and the mean velocity of the entire wave, obtainable through cross-correlation techniques (Comiti et al., 2014). Another example of applications of the cross-correlation to natural hazards is the assessment of the time lag between rainfalls and landslide displacements (Lollino et al., 2002).

The processing of the ground vibration signal has also further purposes. As an example, it allows to better distinguish between debris flows and other types of field and torrent processes that may occur in a debris flow prone basin (i.e. debris floods, rockfalls, slope failures, etc.) (Abancó et al., 2014). The distinction can be based, in fact, on the form of the processed signal that appears to be significantly different according to the different process that has produced it (Figure 8).

Last but not least, the processing of the ground vibration signal also allows to more easily defining eventual warning algorithms (Abancó et al., 2014; Arattano and Marchi, 2008). In fact it is much easier and sound to establish warning thresholds in terms of number of impulses or values of amplitude than defining thresholds directly for the raw signal.

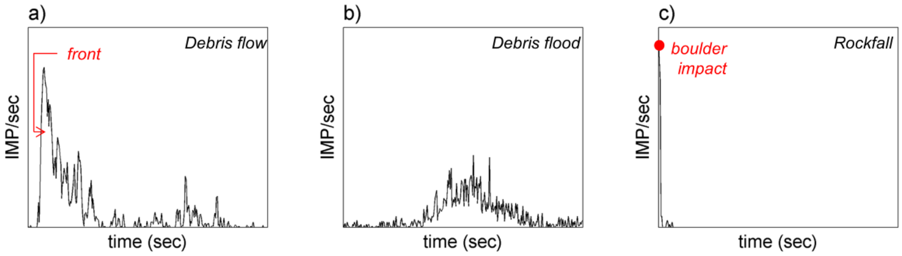

Figure 8 - Typical shapes of the impulses per second (IS) signal registered during a debris flow (a) debris flood (b) and rockfall (c). Horizontal and vertical scales are the same in the three cases (modified after Abancó et al., 2014).

It must be emphasized, however, that the processing of the raw data of the geophone through the mentioned methods produces a loss of information. The information regarding the frequency of the signal is lost, for example, in both methods. The method of impulses also produce a loss of information regarding the intensity of the signal, while the method of amplitude only maintains an information regarding its mean value for each second of recording. To avoid this loss of information and still record a limited number of data, the processed signal can be analyzed through specific algorithms to detect the occurrence of a debris flow and then trigger a full recording of the geophone raw data for the specific, brief time span during which the debris flow takes place in the torrent (Abancó et al., 2014). Debris flows are in fact relatively brief phenomena, usually lasting few tens of minutes. For such brief periods of time the power supply provided by solar panels and the storing capabilities of data loggers may allow a recording at higher frequencies as those required to conveniently detect debris flows mentioned above (about 160-200 Hz). Such type of recording, realized through a triggering threshold, has been adopted and tested for some of the geophones installed in the Rebaixader Torrent (Abancó et al., 2014) and also in the Illgraben (Badoux et al., 2008; Hürlimann et al., 2003).

Given all these reasons and needs for which the processing of the seismic raw signal derived from geophones is required, it becomes clear that the existing methods of data processing should be better understood. Their origin and rationale, the effects that they produce on the original signal and their results should be more deeply examined and possibly compared to better know what the monitoring/warning equipment will deliver because of their implementation on board.

There are currently some field data sets regarding debris flows that have been collected in specific instrumented areas using these different methods of seismic data processing (Abancó et al., 2012, 2014; Badoux et al., 2008; Comiti et al., 2014; Marchi et al., 2002). These data sets could be much more valorized if a deeper understanding of their meaning could be obtained analyzing the methodologies applied to collect them. This would be certainly worthwhile, given the efforts that have been carried out and the time that has been spent to collect them.

In this paper we will discuss the currently most used methods of GVD data processing: the methods of amplitude and impulses are presented, describing their origin, the history of their application and their main advantages and shortcomings. Then the results of the application of the two methods to the ground vibration data of a debris flow event will be compared and discussed. This will provide means for decision to researchers and technicians who find themselves facing the task of designing a debris flow monitoring installation or a warning equipment in the field based on the use of ground vibration detectors. Measurements procedures that make use of geophones, in fact, still need standardization and further research to exploit all the possibilities that they may offer (Arattano et al., 2015b).

3.2.2 The method of Amplitude

The method of amplitude requires the transformation of the analogical voltage signal that comes out from the geophone into a signal digitalized at a certain frequency F and then calculates the mean of the absolute values obtained, for each second of recording, from the digitalization, according to the formula:

$$A = \frac{\sum_{i=1}^{F} |v_i|}{F} \quad (4)$$

In (4) A is the amplitude and v_i is the ground oscillation velocity, obtained multiplying the voltage values, sampled at the frequency F, by an instrumental transduction constant. A value of A can then be stored each second by the data recorder device, providing a recording of the signal at a frequency of 1 Hz.

The method was originally employed by to process the raw data recorded through some seismic devices for two debris flows occurred in 1996 in the Moscardo Torrent (Arattano and Moia, 1999). The data had been originally recorded in analogical form on a magnetic tape and in that form they could not provide relevant and useful information (Figure 6). Thus the calculation of the Amplitude was performed to try to reveal signal features that might have helped in analyzing the data and exploiting them for any type of measurement. The calculation of the amplitude appeared immediately useful since it revealed a shape of the ground vibration recordings that closely resembled the recordings of the stage sensors (Figure 9).

In particular the method showed the presence of a well-defined peak in the seismic signal, lasting only one second and thus identifiable with extreme precision. This latter peak occurred at the passage of the main front at the cross section where the sensor was installed and corresponded to the maximum stage value present in the hydrograph recorded with the ultrasonic sensor. The method of amplitude proved also its efficacy in revealing the entire debris flow wave form, including the existence of eventual secondary surges behind the main front. The capability to detect the passage of the main debris-flow front and the subsequent surges allowed the use of two seismic sensors for an estimation of their velocities. These latter velocities can be obtained as the ratio of the distance between two seismic sensors and the time lag elapsed between the appearance of the different surge peaks in the two graphs. Therefore the use of seismic sensors provided an auxiliary method for the estimation of mean velocity that could have been employed in all those cases in which the use of stage sensors were not feasible (steep slopes of the torrent that impeded the installation of sustaining structures, frequent bank erosions that might have destroyed these latter sensors, etc.).

Processing the raw data with the calculation of the amplitude for a number of debris flows recorded in the Moscardo Torrent allowed several interesting findings. It allowed to reveal, for instance, that a well defined debris flow front was not always present upstream of the fan apex (Arattano, 2003). A similar observation has been recently made also by Abancó et al. (2014), processing the seismic data with the method of impulses.

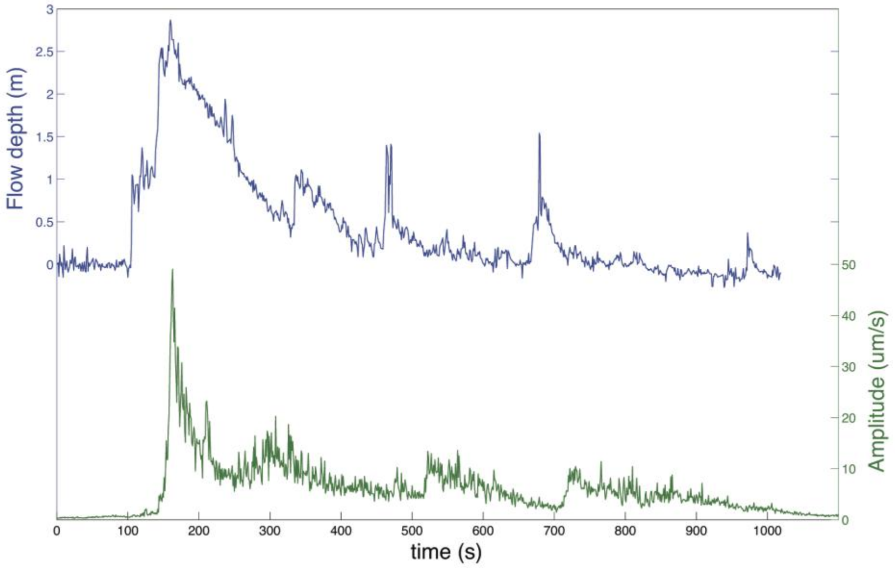

Figure 9 - Comparison of a hydrograph recorded through ultrasonic sensors on the fan of the Moscardo Torrent and the amplitude-vs-time graph recorded upstream of the fan apex for the same event (modified after Arattano and Moia, 1999).

In 1996, in the Moscardo Torrent, there was no need to reduce the amount of data since the recording was performed continuously with the magnetic tapes nor there was any particular need to filter the ground vibration noise. Only with the advent of the digital data logger and the abandonment of the analogical recording the method of amplitude provided, in the Moscardo Torrent, also a mean to simplify the signal reducing the recording frequency (Arattano et al., 2012). The method of amplitude, in fact, diminishes the power consumption of the system and the amount of data gathered without losing significative time in data transformation or filtering, exactly like it happens for the method of impulses. Moreover it simplifies the data analysis and allows an easier implementation of algorithms for detection of debris flows based on the geophone's signal. However the method has some important shortcomings, since it definitely loses fundamental information regarding the recorded signal that may be essential for its complete seismic characterization. As it occurs for the transformation of the ground vibration signal into impulses, the information on frequency content of the signal becomes in fact unavailable after the calculation of the Amplitude. As far as the intensity of the signal is concerned, which was completely lost with the method of impulses, at least its mean value is recorded, but information regarding its maximum values is no more available after the transformation. In recent years, the method of amplitude was adopted in two other instrumented basins located in the Italian Alps, the Gadria (Comiti et al., 2014) and the Marderello (Turconi et al., 2015).

3.2.3 The method of Impulses

The method of impulses is based on a transformation of the geophone's output voltage into a binary signal consisting in impulses. The impulse signal is captured by the data recorder device (data-logger or PC), where a counter stores the number of impulses per second. The transformation into impulses has two main purposes: a) to the filter the ground vibration noise, and b) to simplify the signal. The filter is done by means of an amplitude threshold, which acts as a critical value to distinguish between the ground vibration noise of the site and the higher abnormal values associated with torrential processes. When the amplitude threshold is exceeded, an impulse is generated, which lasts until the signal crosses the line of zero amplitude (Figure 10). The impulse signal takes two possible values: 0 V when the threshold's voltage is exceeded and 12 V (power supply value) when the voltage is under the threshold.

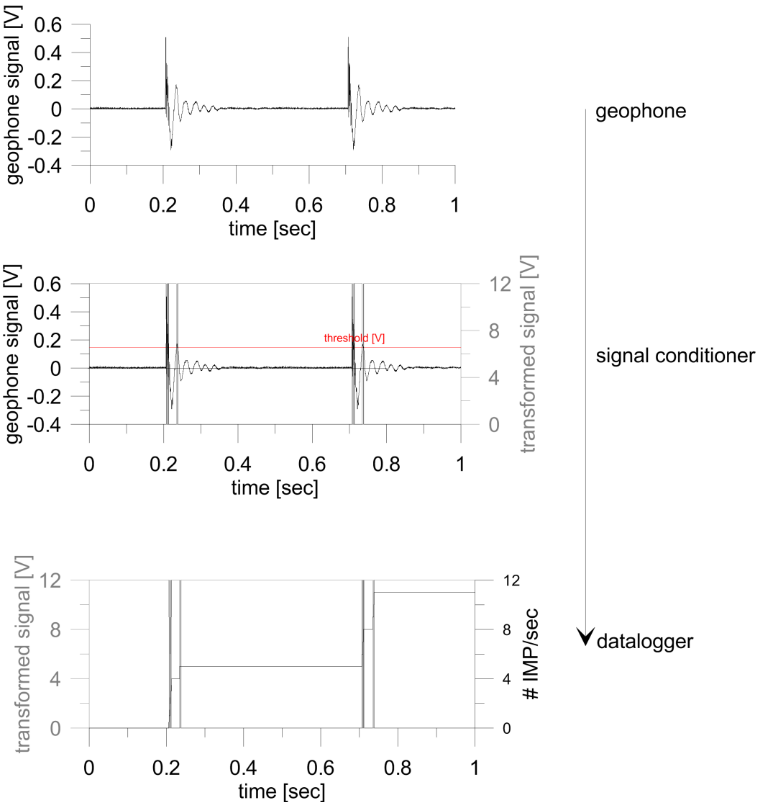

Figure 10 - Process of signal transformation from the geophone to the datalogger (after Arattano et al., 2014).

The signal conditioning was implemented into an electronic circuit board, where the whole transformation is immediately carried out (Abancó et al., 2012). The geophone is connected to the circuit board by wire and the circuit board receives analogically the signal from the geophones. It transforms it into an impulse signal in accordance with the amplitude's threshold. Then, the signal is sent to the data recorder device also by wire, where it is captured digitally by a pulse counter. The circuit board is protected from voltage spikes (by a voltage suppressor) and is equipped with a voltage converter to transform the input power supply voltage from the datalogger (normally 12 V) into +/-5V, which is the working voltage of the circuit. The circuit board is operable with frequencies up to 2 kHz, which widely includes the frequencies of the signals induced by debris flows or other torrential processes.

One of the most relevant advantages of the methodology is that the sampling rate of the datalogger can be reduced to 1 Hz, instead of the high sampling rates required in the use of other ground vibration recording techniques. The reduction of the sampling rate, at the same time, diminishes the power consumption of the system and the amount of data gathered. It simplifies the data analysis, the transmission by GPRS or other wireless technologies, and the implementation of algorithms for detection of debris flows based on geophone's signal. However, the method of impulses has also shortcomings. The major drawback is the necessity of accurately calibrating the voltage threshold. The inappropriate calibration of this key parameter can induce even the loss of events (if it is too high; see Abancó et al., 2012). Although the understanding of the seismic response of torrential processes has strongly improved in recent time (Arattano et al., 2012; Huang et al., 2007) and even some important outcomes on the threshold definition have been obtained (Abancó et al., 2014), a period of testing and the expert supervision in order to correctly perform the calibration is still required. Another drawback is the fact that due to the transformation of the ground vibration into impulses information on signal's frequency content or amplitude are lost. These parameters may be essential for the complete seismic characterization of the signals.

The method of impulses has its origin in the seismic monitoring of bedload transport. The Swiss Federal Institute for Forest, Snow and Landscape Research developed this technique during the late 1980's to monitor the bedload transport in three experimental catchments of Central Switzerland using hydrophones (Rickenmann, 1994). About one decade later, the technique was adapted and implemented for the monitoring of debris flows. While in bedload transport monitoring the method of impulses is used to quantify sediment rates, in debris flow monitoring, the main purpose is the detection of the flow near the location of the geophone, in order to describe its propagation along the torrent and to calculate the mean flow front velocity. The method of impulses has been used in several Swiss debris-flow monitoring sites, both for scientific observation and alarm purposes (Hürlimann et al., 2003; Badoux et al., 2009; Graf et al., 2012).

Since 2009, the method of impulses is also used in three Pyrenean debris flow catchments (Hürlimann et al., 2011). Recent studies demonstrated that the Impulses per Second (IS) signal could be used also for the characterization of the debris-flow events and not only for the calculation of the mean front velocity (Abancó et al., 2012, 2014). Moreover, the experience in the Rebaixader Torrent suggests that the method of the impulses may be also useful for the monitoring of other types of torrential processes besides debris flows, such as debris floods or rockfalls (Hürlimann et al., 2012). It is planned for the near future that the IS technique will be installed in debris flow torrent in Italy (Fiammes Torrent, Alessandro Simoni, personal communication, July 3rd, 2013). Moreover, it is currently under consideration the installation of signal conditioners for the transformation into impulses for the detection of snow avalanches in Norway (Klaus Trondstad, personal communication, September 2nd, 2013).

3.3 Case study: the Rebaixader Torrent (Spanish Pyrenees)

The Rebaixader Torrent (Figure 11) is located in the Axial part of the Central Pyrenees. The source zone is a thick till deposit over bedrock of slates and phyllites. The till corresponds to a lateral moraine of the glacier that occupied the Noguera Ribagorçana Valley during the Last Glacial period. 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 annual precipitation in this area is between 800 and 1200 mm.

The Rebaixader Torrent has shown unusually high debris-flow activity for the Pyrenees, since large events (several thousands of cubic meters) can be expected every year (Hürlimann et al., 2013). This high activity and its short distance between the source area and the channel zone make this torrent advantageous for monitoring activities. The basin is equipped with 8 geophones, located along the flow path. The geophones were placed in safe places along the torrent. The separation between them was chosen in order to distinguish the flow front in each geophone consecutively. Only in special cases (Geo5 & Geo7 and Geo3 & Geo3b) were located next to each other to focus on the local effects of the mounting conditions.

Several types of processes and a great number of events have been recorded in the Rebaixader monitoring site over the last years (Hürlimann et al., 2013). As stated in

Abancó et al. (2014), the shape of the IS signal has been identified as a key parameter for the distinction of torrential processes and for the characterization of the events. In this study the debris flow event occurred in the Rebaixader Torrent on July 4, 2012.

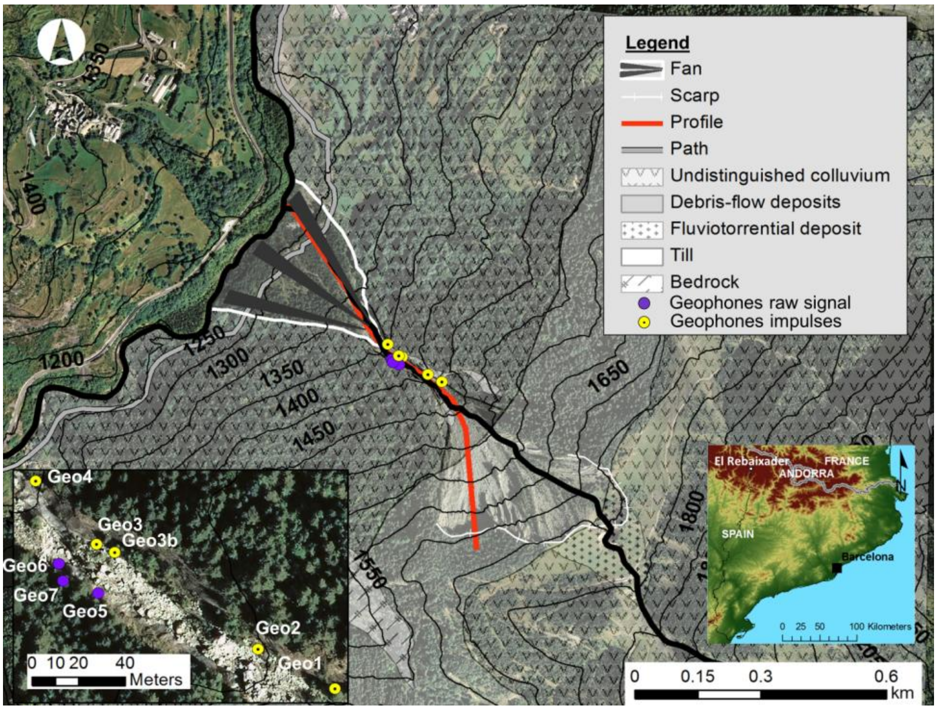

Figure 11 - Geomorphological map of the Rebaixader Torrent (Arattano et al., 2014). Inset, detail of the geophones area and the location of the Rebaixader Torrent (background image: air borne data collected by the Catalan Cartographic Institute in 2008).

3.4 Results and discussion

The two methods of data processing that we have examined in the previous sections have been applied to process the raw data recorded by three geophones installed along the left bank of the Rebaixader Torrent, on July 4, 2012, when a debris flow event occurred in the catchment. In Figure 12, the three Amplitude vs time graphs (second row) were obtained processing the raw data (first row) recorded by the three geophones Geo5, Geo7 and Geo6 installed along the torrent (Figure 11). Below, each Amplitude graph, three different curves displaying the number of Impulses per second vs time are shown for comparison, which were obtained with different threshold values for the counting of the impulses. The comparison highlights interesting details and offers a chance for some comments on the two methods adopted.

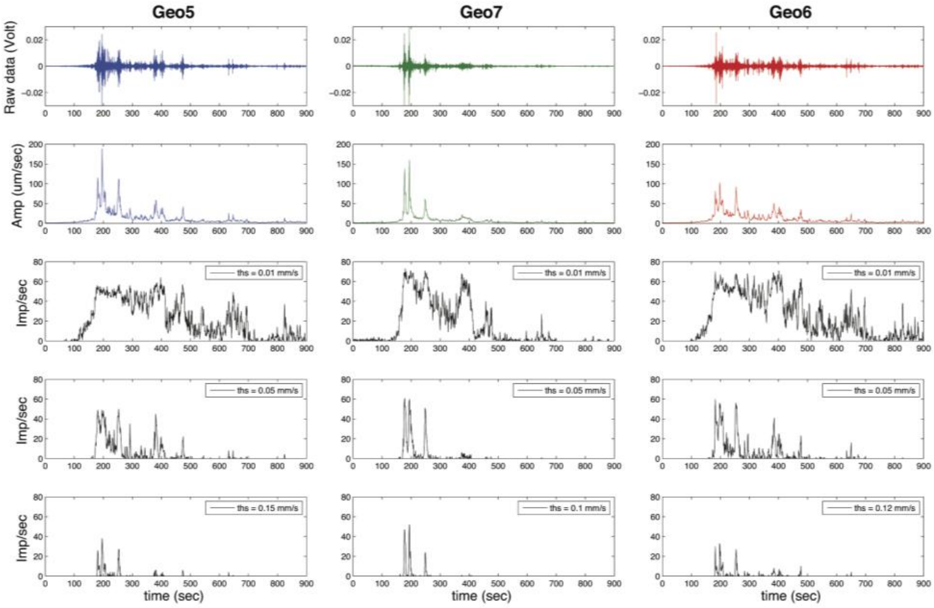

Figure 12 - The raw data (sampling rate = 250 Hz), the Amplitude graphs and three Impulses curves produced applying different threshold values of the debris flow event occurred in the Rebaixader Torrent on July 4, 2012.

All the three amplitude graphs display a common, recognizable feature: the presence of three different peaks in the first phase of the curve that have values of amplitude reaching 100 µm/s or greater (with the exception of the third peak at geophone Geo7). These peaks may be ascribed to the occurrence of three different, distinct surges in the first phase of the event. The second peak appears to be, in all the three graphs, higher than the remaining two. On the contrary the first and the third peak appear to have similar values for geophone Geo5 and Geo6, while in the curve of geophone Geo7 the third peak appears much lower than the first two.

It has been already observed that a proportionality exists between the amplitude and the stage (see Figure 9). In the event occurred on July 4, 2012 in the Rebaixader Torrent, this proportionality could be observed only for the first of the three surges. Unfortunately, the hydrograph for this event couldn’t be recorded entirely due to a malfunction of the ultrasonic device after the pass of the first main surge (Figure 14).

Behind the first three peaks, the Amplitude graphs of geophone Geo5 and Geo6 display a series of further, smaller peaks: at least three of these peaks can be easily identified in Figure 10. On the contrary, the smaller peaks following the first three surges in the graph of Geo7 are barely visible. This latter occurrence might be explained by differences in site specific factors (Abancó et al., 2014): the ground vibrations produced by the three further, small surges that followed the first three might have been attenuated by the greater distance or the major thickness of soil they had to travel to reach Geo7. However this attenuation did not occur for the first three peaks: they are even larger at Geo7 than they are at Geo6.

A possible explanation for all these occurrences could be the different frequencies of the ground vibration produced at different stages of the debris flow wave. Huang et al. (2007) observed that, at the surge peak, frequencies range between 10–30 Hz while at the flow tail they usually become higher, ranging between 60–80 Hz. Indeed, the smaller surges occurring in the tail of the July 4, 2012 debris flow wave have a higher frequency content than the first three surges (Figure 13). Moreover, it is well known that higher frequencies attenuate faster with distance. This may also explain the lower intensity of the third of the first three surges occurring in the frontal part of the debris flow. In particular for Geo7, this third surge seems to have a higher frequency content than the second one. The spectrograms of Figure 13 have been calculated using the short time Fourier transform (STFT), a Fourier-related transform used to determine the sinusoidal frequency and the phase content of local sections of a signal $x(t)$ changing over time:

$$STFT_x(\tau, f) = \int_{-\infty}^{+\infty} x(t) \cdot g(t-\tau) \cdot e^{-j2\pi ft} dt \tag{5}$$

Other reasons that might explain the different intensities measured by the three geophones might concern their method of installation. Geophone Geo5, in fact, is directly installed in bedrock. This could account for the greater values of the amplitude of the first three surges recorded by this sensor. Site effects and the method of installation might have played a role also in the response of the Geo7. All these observations testify the fact that the response of a geophone depends on several site-specific aspects and the response of each geophone should therefore be checked after installation, possibly at the occurrence of the first debris flow, to better understand its behavior. This also emphasizes the importance of a standardization of the methods of installation of geophones and other ground vibration sensors when they are employed in the seismic monitoring of debris flows (Arattano et al., 2015b).

Coming now to the graphs of the impulses of Figure 12, a first observation that can be done, observing the results of the application of the different thresholds, is that a too low threshold may completely impede to differentiate the dimensions of the different surges that occurred in the flow. It is well known that the choice of a threshold that is too low conduces to lose the possibility to distinguish the different phases of the debris flow event (Abancó et al., 2012). 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. However, the threshold could be high enough to avoid a flat graph, but remain still too low to allow a differentiation of the dimensions of the eventual surges that compose the debris flow. In fact in all the three impulse vs time graphs obtained for a threshold of 0,01 mm/s the first three peaks are almost indistinguishable or have the same value. The fourth and fifth peaks are even larger than the first three at Geo 5 and Geo6.

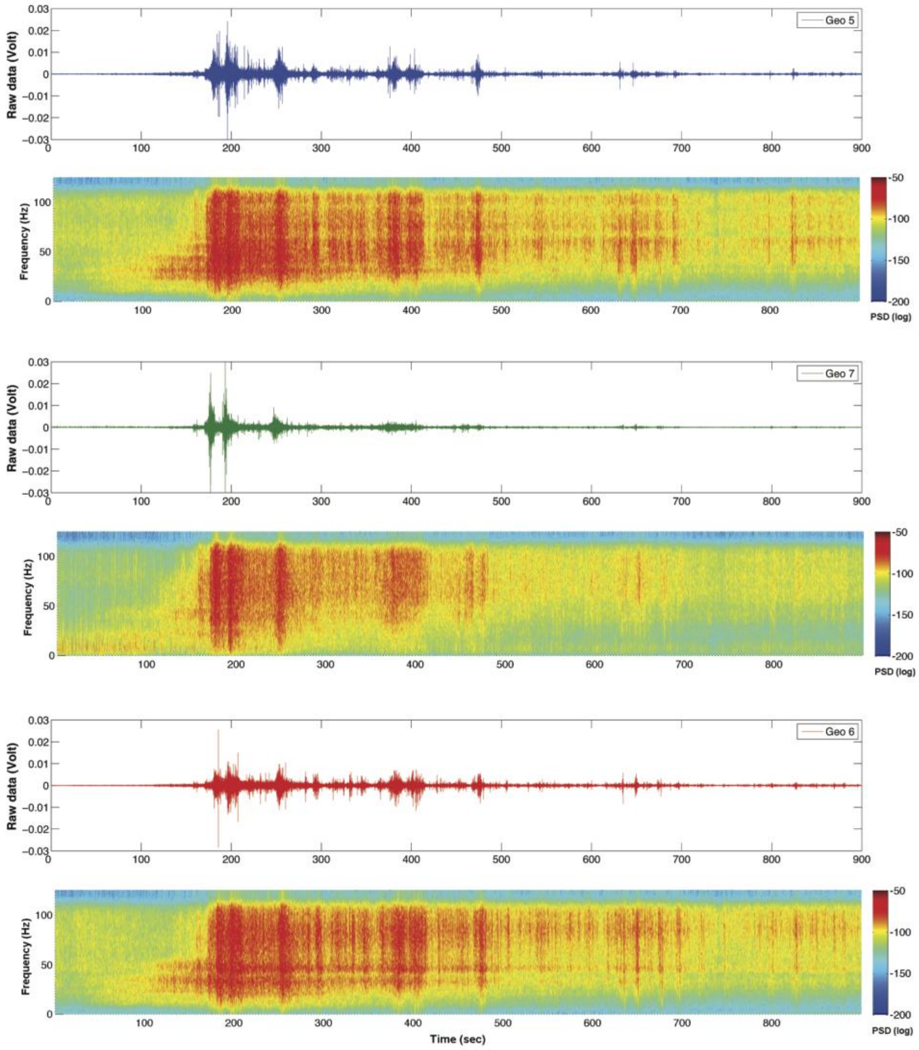

Figure 13 - Spectrograms derived from the 250-Hz raw data of the debris-flow event occurred in the Rebaixader Torrent on July 4, 2012.

It is worth noticing that in the graph of Geo7 the peaks that follow the first three peaks present in the frontal part of the event become clearly visible with the application of the method of impulses with a threshold of 0,01 mm/s, where they were just barely detectable in the amplitude vs time graph. Rising the threshold, a better differentiation becomes possible: in fact in Figure 12, with a threshold of 0,05 mm/s, the peaks that appear behind the first three display smaller dimensions in all three graphs. However, in order to display proportionality between the different surges similar to that one observed in the amplitude vs time graphs, it is necessary to adopt higher thresholds. In particular, to emphasize this similarity in the three traces corresponding to the three first surges it is necessary to adopt a specific threshold for each geophone. For Geo5, the threshold that produces peaks of the impulses that have about the same proportionality between them as that observed in the amplitude vs time graphs, is 0,12 mm/s; for Geo7 it is 0,1 mm/s and for Geo6 it is 0,15 mm/s. The possibility to find thresholds that allow to reveal a proportionality between the peaks of the number of impulses that is similar to that observed in the amplitude vs time graphs, means that the “information” regarding the relative dimensions/intensity of the recorded surges is contained in the raw data recorded. This information can be extracted and revealed with both methods, but the method of impulses requires a correct choice of the threshold, while the method of amplitude directly displays the relative dimensions/intensity of the recorded surges.

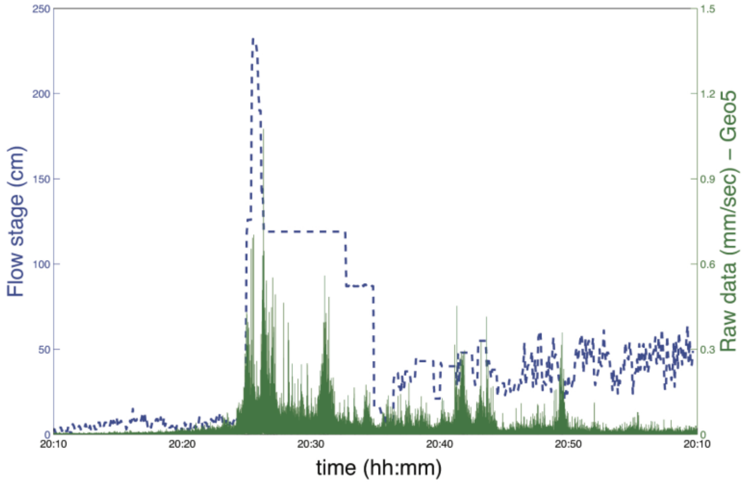

Figure 14 - Ground vibration and hydrograph data of the event occurred in the Rebaixader Torrent on July 4, 2012.

It must be also noticed that with the highest thresholds chosen in Figure 12, the smaller surges that follow the first three that are present in the frontal part of the flow become practically invisible. Therefore it is possible that, looking for a better differentiation of the different phases and surges of the flow, some characteristics of the event get completely lost. It would appear from these results that the method of impulses may occasionally alter the proportionality among the different surges of an event, if too low a threshold had to be chosen, or lose some minor flow characteristics if a high threshold were adopted. Furthermore, the raise of the threshold value produces a progressive decrease of the number of impulses. In Figure 12 the peak impulse values range from 70 IMP/sec (threshold = 0.01 mm/s) to 40 IMP/sec (threshold = 0.1 mm/s). However it is difficult to establish *a priori* which is an optimal threshold because the latter depends by many factors like the distance of the sensor from the torrent, the method of installation (in the ground, on rock surface, in concrete) and the geophone features.

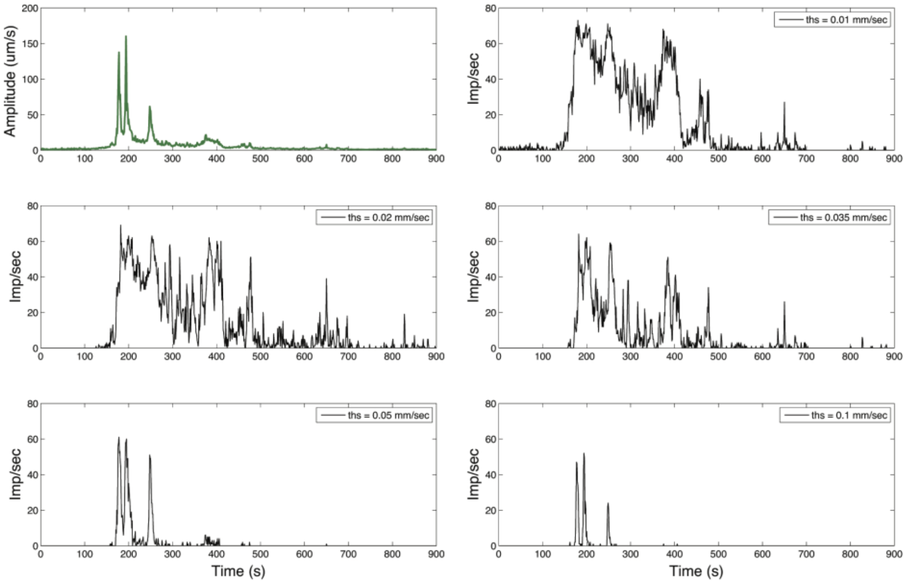

Figure 15 - The Amplitude graph and five Impulses curves produced applying different threshold values on the raw seismic data recorded by the geophone 7 in the Rebaixader basin on July 4, 2012.

In Figure 15 the curves produced applying five different threshold values are reported for the geophone number 7. Two further thresholds (0.02 and 0.035) were used to emphasize the strong effect that the choice of the threshold exerts on the signal shape. It is possible to notice, in particular, how the shape and the value of the peak located close to t = 400 s are considerably affected by the threshold used to draw the curve. As already stated by Abancó et al. (2014) the choice of the threshold is also of great importance to detect the precursory surges of a debris flow event. These latter surges appear in the time series obtained with the lowest thresholds, and almost disappear adopting higher thresholds. Therefore the signal shape is considerably affected by this threshold-effect: a little change of the threshold may significantly affect the signal shape. Since one of the uses of the methods of signal processing that we are discussing is precisely the revelation of signal forms that may help in recognizing and distinguishing debris flows from other types of torrential processes, this significant dependence of the form of the curves of impulses/sec from the threshold should be taken into account.

3.5 Conclusions

There are several reasons to process the raw signal coming from a geophone installed along a reach of a mountain torrent that has recorded the passage of a debris flow. First, the reduced storing capabilities and the limited power supply available in the high mountains environment where geophones are usually installed for monitoring or warning purposes require a reduction of the amount of data to be recorded. Both the method of amplitude and the method of impulses perform well for this purpose, allowing to reduce to 1Hz the recording frequency. The method of impulses also allows filtering the background noise, while the method of the amplitude still records a mean value of this latter noise. Secondly, the processing of the geophone raw signal also allows identifying more easily the algorithms that are needed to detect the arrival and occurrence of a debris flow. In fact the algorithms proposed in literature so far are based on the processing of the raw data (Badoux et al., 2009) in particular through the method of impulses (Abancó et al., 2014).

The processing of the geophone signal is also very useful 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. In the examined data this occurred, for instance, for one of the geophones (Geo7): the amplitude vs time graph did not display some of the minor subsequent surges that followed the frontal part of the event. This may depend on the method of installation of the sensor on the ground and on its distance from the torrent bed.

The limited number of debris flow monitoring sites worldwide and the great difficulties in collecting reliable field data has made difficult and delayed the standardization of methods, devices, techniques and procedures for debris flow monitoring and data collection. This is particularly true for the monitoring of debris flow through seismic devices. Some of these data are processed with the transformation of the signal into impulses and some other with the transformation into amplitude. The best way to exploit at most data recorded so far is probably to use both amplitude and impulses methods in every existing and future installation. More field evidences and further investigations are therefore needed to better specify the limits of the discussed methods of data processing and to better understand them. In particular the comparison of the geophone data with the variation of the flow stage might greatly help in improving the knowledge regarding the considered methods.

4 Detection of torrential processes with a seismic monitoring network

4.1 Introduction

Passive seismic monitoring techniques are increasingly adopted to detect seismic sources induced by slope deformation, landslide propagation and torrential processes: signal processing can provide relevant information on the dynamics of flows and unstable slopes and may provide timely warning or allow the identification of precursory patterns that might lead to collapse (Amitrano et al., 2005; Coviello et al., 2015b; Feng, 2012; Suriñach et al., 2005). When signals induced by large landslides are detected with broadband seismometers, even located at distance of kilometers, the seismic inversion and the spectral analysis may also allow a preliminary characterization of the phenomenon (Allstadt, 2013; Dammeier et al., 2011; Deparis et al., 2008; Iverson et al., 2015; Moretti et al., 2012; Suriñach et al., 2005; Yamada et al., 2013). As a consequence, currently most site-specific monitoring systems of active landslides or instable slopes often integrate, among the different monitoring devices, a ground vibration detectors (GVDs) array.

Among the different natural phenomena that have been monitored through GVDs, there are debris and mud flows. Debris flows and mud flows are among the most dangerous and destructive natural phenomena that may occur in mountain environments. They can cause severe damages to human settlements and infrastructures that are built too close to mountain torrents or on their alluvial fans (Arattano et al., 2010). Monitoring these phenomena in instrumented catchments through different type of devices and sensors allows the collection of field data that can provide an important comparison with the geomorphologic and topographical surveys of erosion, sediment supply and channel evolution (Berti et al., 2000; Cui et al., 2005; Hürlimann et al., 2011; Marchi et al., 2002; McCoy et al., 2010; Suwa et al., 2011). Monitoring data and the inferred quantification of the transported sediment are also of crucial importance for hazard assessment, land-use planning and design of torrent control structures, including early warning systems (EWSs). For all these purposes, local seismic monitoring networks are usually installed in specific monitoring sites together with other typologies of sensors. The possibility to detect debris flow from a distance, however, is an important advantage of GVDs. Most monitoring devices need in fact to be installed in the channel bed or very close to it to properly work (e.g. stage sensors, force plates, pendulums), with consequent greater danger to be destructed by debris flows.

The seismic monitoring of debris flows has been performed worldwide since many years (Berti et al., 2000; Bessason et al., 2007; Comiti et al., 2014; Cui et al., 2005; Huang et al., 2007; Hürlimann et al., 2011; Kogelnig et al., 2011; Lahusen, 2005; Marchi et al., 2002; Navratil et al., 2013; Suwa et al., 2011). Debris flows are in fact known to produce strong ground vibrations that can easily be detected by placing an array of seismic detectors at a convenient distance from the torrent bed. Geophones, particularly mono-axial (1-D), vertical geophones, are the most commonly used GVDs, for they robustness, low power consumption and relatively low cost (Arattano et al., 2015b; Hürlimann et al., 2011).

Recently some investigations concerning the use of seismic devices for the monitoring of mud flows have also been started (Turconi et al., 2015). Mud flows are phenomena very similar to debris flows but their mixtures involve significantly greater water content relative to the source material and a smaller concentration of boulders with respect to debris flows (Coussot et al., 1998; Hungr et al., 2001). These properties have an effect on the results of seismic monitoring, which can be significantly different than those of debris flows. In fact, the smaller number of coarse particles entails the production of lower impact forces and this impedes the generation of ground vibrations as strong as in case of debris flows. In addition, the ground vibration signals produced by mud flows may also have different frequency ranges and different peak frequencies. These different behaviors should be investigated, not only for scientific purposes, but also because they might lead to the choice of different parameters and algorithms when GVDs are used for warning purposes.

Recent experiences in the Central Pyrenees (Spain), carried out mainly for the monitoring of debris flows, suggest that the detection of ground vibration through GVDs installed outside the channel may be also useful for the monitoring of other types of processes that can occur both in the channel or out of it, such as debris floods and rock falls (Abancó et al., 2014; Hürlimann et al., 2012). It must be noticed, to this regard, that recently, following a pioneering work by Govi et al. (1993), an increasing number of contributions have also dealt with the detection of the seismic activity related to bed load transport variations (Burtin et al., 2011; Díaz et al., 2014; Hsu et al., 2011; Rickenmann et al., 2012; Travaglini et al., 2015).

The monitoring of torrential processes through GVDs, in particular, may allow the estimation of several important parameters, such as the debris flow mean front velocity and the velocity of other singularities, such as the secondary waves that may occur behind the front. The velocity of the entire debris flow wave may also be estimated applying the cross-correlation technique to the ground vibration recordings (Arattano and Marchi, 2005).

Currently, several research efforts are devoted to investigate the potential of seismic devices for the development of debris flow EWSs (Abancó et al., 2014; Badoux et al., 2008; Huang et al., 2007). The first attempts to design a geophone-based warning system for debris flow rely on signal intensity thresholds. In the Illgraben catchment (Badoux et al., 2008), the system sends a first alarm and activates flashing alert lights and acoustic signals on the fan area downstream when an impulse threshold condition is exceeded on a single sensor. Recently, a specific testing field for debris flow EWSs has been equipped in the Gadria basin (Eastern Italian Alps) to provide a site where different types of warning algorithms can be tested. In fact, the use of geophones as warning devices still present several aspects that need to be better investigated and understood, and a need for standardization of the adopted methodologies is urgently needed (Arattano et al., 2015b).

There is also an open discussion concerning the best methods to process the seismic raw data for their interpretation and use in warning algorithms (Arattano et al., 2014) or regarding the possibility to employ geophones in conjunction with other types of devices to build more robust and reliable warning systems (Schimmel and Hübl, 2015). One of the still open issues concerns the effects that torrential processes different from debris flow may produce on the seismic signal influencing the warning.

To investigate some of the issues detailed above, seismic monitoring data obtained from two instrumented areas (the Marderello and the Gadria basins, Italian Alps) will be here presented and discussed, with a particular attention to the aspects and the effects that they may have on the design of warning systems.

4.2 Study areas

4.2.1 The left Cenischia valley

The left Cenischia valley (North-western Italian Alps, Figure 16) is incised in massive or foliated Mesozoic rocks, mainly composed by carbonate-rich calcschist interbedded with clayey-arenitic schist. These rocks are steeply dipping downslope and widely overlied by deep-seated slope collapse deposits and partly by detrital talus. A north-south oriented fault system has resulted in a very complex network of rock joints and cracks. The bedrock of the study area is a succession of intensely folded and faulted calcschist sequences irregularly lying upon silicate marble. Ophiolites are tectonically interposed in the basal part of silicate marble which crops out in the South-Eastern part of the Cenischia valley. Calcschist's complex is about 600 m thick and form the highest peak in the area (Rocciamelone Mt., 3538 m); silicate marble sequences attain a maximum thickness of about 150 m. Their lower limit is locally underlined by 10-meter-thick layers of dolomitic marble and tectonic breccia.

Table 2 - Topographic parameters of the five sub-catchments of the left Cenischia valley.

Catchment	Main stream length (km)	Average slope basin (%)	Altitude max (m a.s.l.)	Altitude min (m a.s.l.)	Area (km^2)
Malo	3.5	70	3505	1041	5,2
Gioglio	5	71	3384	866	7,4
Claretto	5.8	74	3317	900	4,1
Marderello	5.7	75	3538	900	6,6
Crosiglione	4.9	65	3100	800	5,8

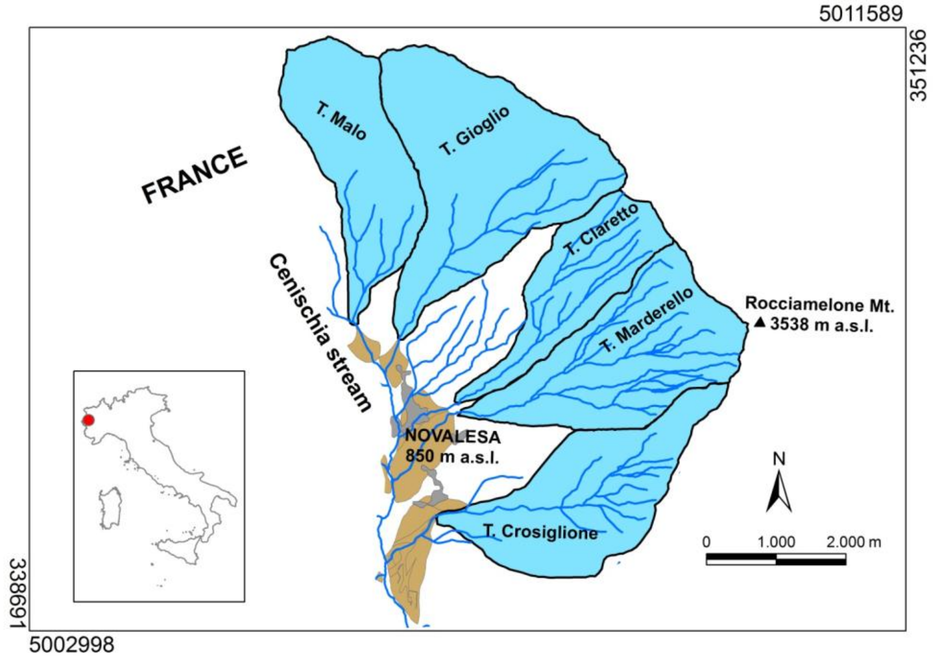

Figure 16 - Location and simplified map of the left Cenischia valley, North-western Italian Alps. Coordinate system: WGS 1984 UTM Zone 32N.

The five sub-catchments composing the left Cenischia valley (Table 2) are well-known for producing frequent debris flow events and other slope instability phenomena (Tropeano et al., 1999). In a dominant landscape thoroughly inherited by deep-seated gravitational slope deformations (DGPV) typically evidenced by double ridges, pinnacles and trenches, the signs of recent rockfall processes are very visible. In the head of the catchments DGPV processes exert their degradational effects increasing the debris potential along the stream incisions where debris flows initiate. The slopes are segmented into several steps originated by morphology and geological structures, this imparts a singular stop-and-go behavior to sediment-gravity flows: the less-inclined stretches are favorable to deposition and temporarily stockage of debris and sediments and alternate with stretches prone to erosion. This produces a series of natural falls even dozens of meters high.

4.2.2 The Marderello monitoring network

The Marderello basin can be considered a perennial source of debris due to the above mentioned conditions (Turconi et al., 2010). The topography of the basin, left tributary of the Cenischia valley (North-western Italian Alps), strongly conditioned by its geological, structural and glacial history, may often induce changes in the composition of the solid-liquid mixture of the debris flows that originate in the upper catchment (Figure 17).

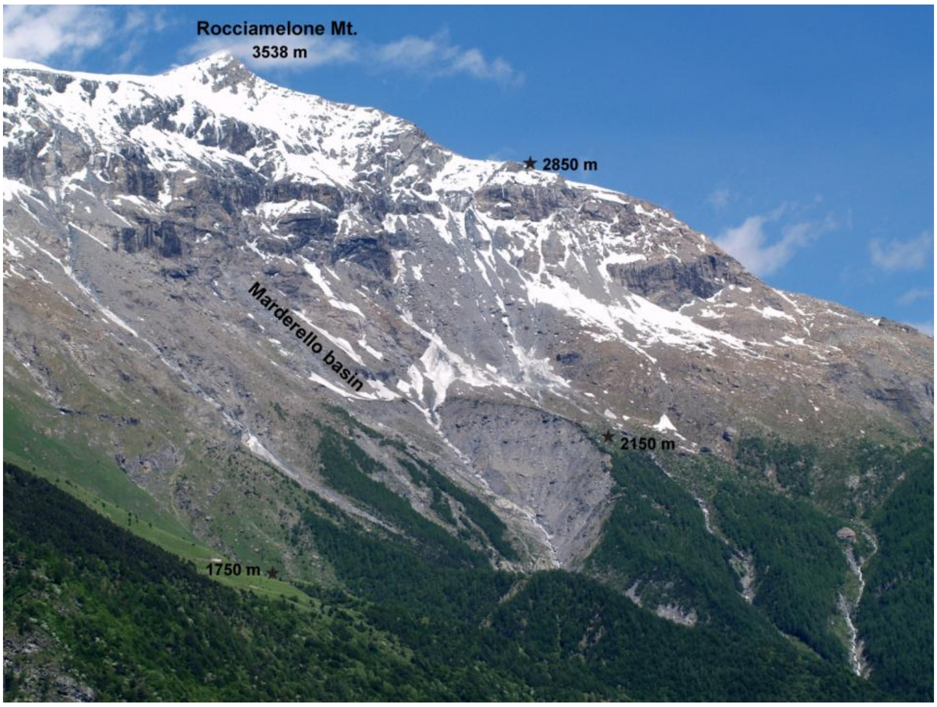

Figure 17 - The upper Marderello basin, view from the West side of the Cenischia Valley. The stars represent the rain gauges location, the monitoring station is located downstream on the alluvial fan (not visible in this picture).

In the intermediate section of the torrent, the succession of canyons and waterfalls operates as a “filter” reducing significantly the grain size and the solid volume percentage in the mixture. This effect imposes significant variation to the sediment transport typology: from a stony debris flow initiating in the upper basin the phenomenon usually evolves in a muddy debris flow or a mud flow on the alluvial fan (Turconi et al., 2015). The Marderello catchment (6.61 km^2) is frequently affected by mud flow phenomena (1 per year, on the average), as a consequence it was chosen as test site. The microseismic network, consisting of 4 vertical geophones (natural frequency of 10 Hz) installed along a straight reach of the torrent, is expected to give indications on the differences of behavior between mud flows and debris flows. The catchment is also equipped with three videocameras, two rainfall stations and an ultrasonic stage sensor (Figure 18). The final goal of the ongoing research activities is to develop and test warning algorithms.

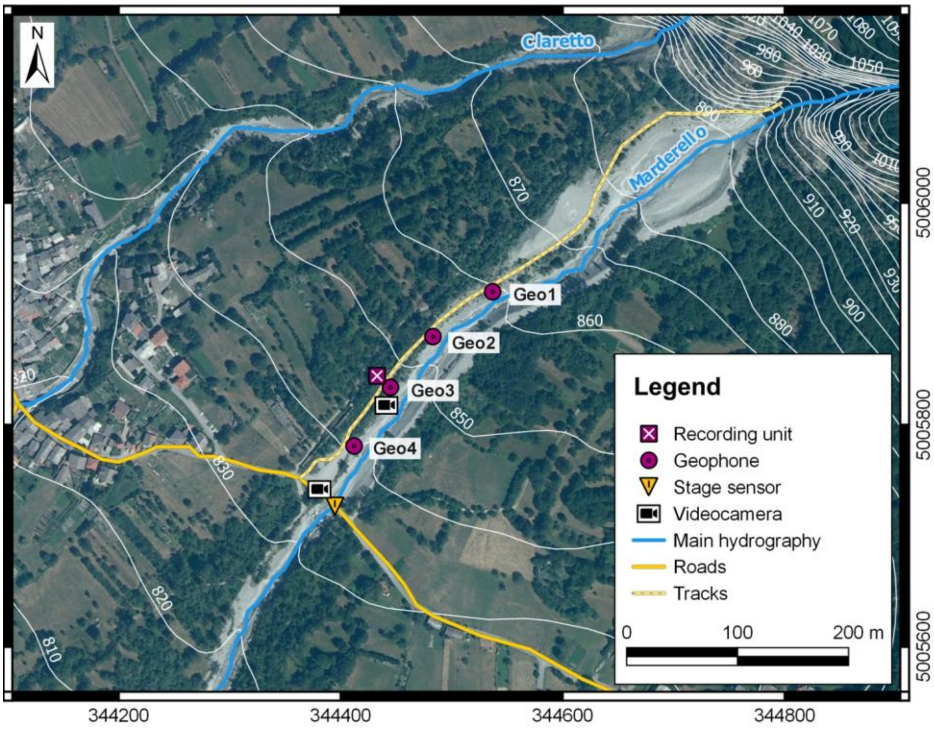

Figure 18 - Plan of the Marderello monitoring station, background image ©2014 DigitalGlobe, coordinate system WGS 1984 UTM Zone 32N. On the left part is visible the village of Novalesa, the monitoring station is equipped along the Marderello torrent, downstream the waterfall and the retention basin.

Since 2013, the method of Amplitude is employed in the Marderello catchment. The recording unit employed in the Marderello torrent has been set up on the basis of the previous seismic equipment employed in the Moscardo torrent (Marchi et al., 2002). A 18-bit Analog-to-Digital (AD) converter process in real time the raw seismic signal detected by four mono-dimensional geophones: the analogical signal is sampled at 100 Hz, the Amplitude is calculated and then recorded in a flash memory card. The raw signal transformation allows a large storage capacity, in fact 1 month of Amplitude data approximately occupy 64 Mb. A very high amplification of the signal (gain = 500) was adopted during the digitizing phase to compensate the expected lower intensity of the signal due to the small number of coarse particles in the mud flow mixture. The method of Amplitude was preferred to the method of Impulses because it allows a better differentiation of the relative intensities of the surges that may compose a debris flow or mud flow wave. This latter characteristic was particularly important in our case, since we are specifically interested in investigating the difference of behavior of mud flows as far as the intensity of the signal produced by them is concerned. The choice of the method was also imposed by the limitations of the hardware employed for the recording: the sampling frequency of the signal that the unit could perform was in fact too low to grant a satisfactory detection of the impulses.

4.2.3 The Gadria-Strimm basins

The Gadria–Strimm basins are located in the Vinschgau-Venosta valley, Autonomous Province of Bozen-Bolzano, North-eastern Italian Alps (Figure 19). They have a geology dominated by metamorphic lithologies. In particular, the Ötztal unit and the underlying Campo nappe chiefly consist of gneiss and schist, with subordinate amphibolites, orthogneiss and marble, separated by Permo-Mesozoic metasedimentary rocks. The Ötztal-Campo stack is characterized by fractures trending along N, E, NE and SW directions, and these structural patterns impart a primary control on the spatial structure of the drainage network and influence rock strength. Most of Strimm basin and the upper portion of Gadria basin are underlain by paragneiss of the Mazia unit. The massive kame terraces located along the steep headwalls of Gadria Torrent sit on extremely weathered and fractured bedrock surfaces, which have developed steep ravines and badland-like morphology since the glacial retreat. Such an unstable setup provides a virtually unlimited source of sediment (Figure 20b). For more details on the Gadria-Strimm geologic and geomorphologic settings see Comiti et al. (2014) and therein references.

The two basins (Table 3) join at a filter check dam located near the apex of their large alluvial fan (10.9 km^2). Most monitoring activities focuses on the Gadria catchment, which originates on the average 1–2 debris flow events per year. However, some instrumentation is also installed in the Strimm catchment to enhance the hydrological information on the neighboring catchment. The combination of steep topography, highly deformed/fractured metamorphic rocks and thick glacio-fluvial deposits, sets the conditions for chronic debris flow activity within the Gadria channel network (Comiti et al., 2014).

Table 3 - Topographic parameters of the Gadria–Strimm catchments.

Catchment	Main stream length (km)	Average slope basin (%)	Altitude max (m a.s.l.)	Altitude min (m a.s.l.)	Area (km^2)
Gadria	2.9	79.1	2945	1394	6.3
Strimm	5.7	61.8	3197	1394	8.5

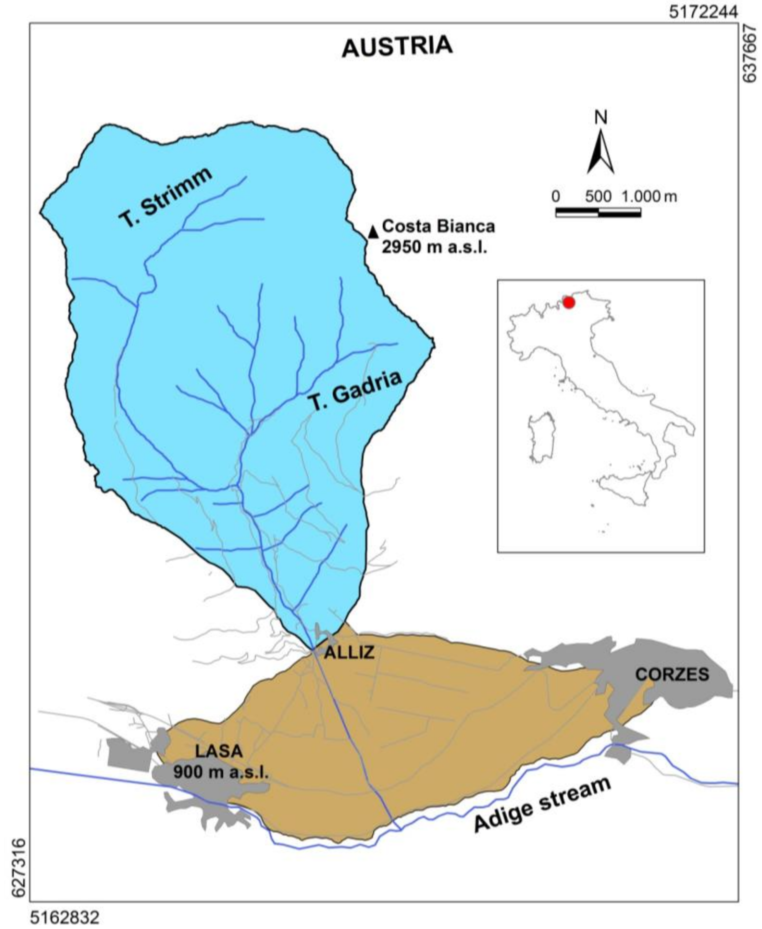

Figure 19 - Location and simplified map of the Gadria–Strimm basins, North-eastern Italian Alps (after Comiti et al., 2014).

In the late nineteenth century, a straight paved channel was built to divert the Strimm–Gadria channel on the fan farther from the village of Laas, which had been flooded and hit by debris flows several times. In addition, consolidation check dams were built along the main channels and their headwater tributaries starting in the early twentieth century. Finally, in the 1970s, a filter check dam with a storage basin of circa 50,000 m^3 was built at the fan apex, just downslope from where now the main monitoring station is located. This work prevents debris flows from propagating onto the fan, but it requires very high maintenance costs for the Province of Bolzano (about 200,000 €/year) due to sediment removal and disposal. In fact, the recent (since 2003), well-documented records of debris flows in the Gadria basin indicate an average of 1–2 events per year, with volumes from 700 to 40,000 m^3 per event (Comiti et al., 2014).

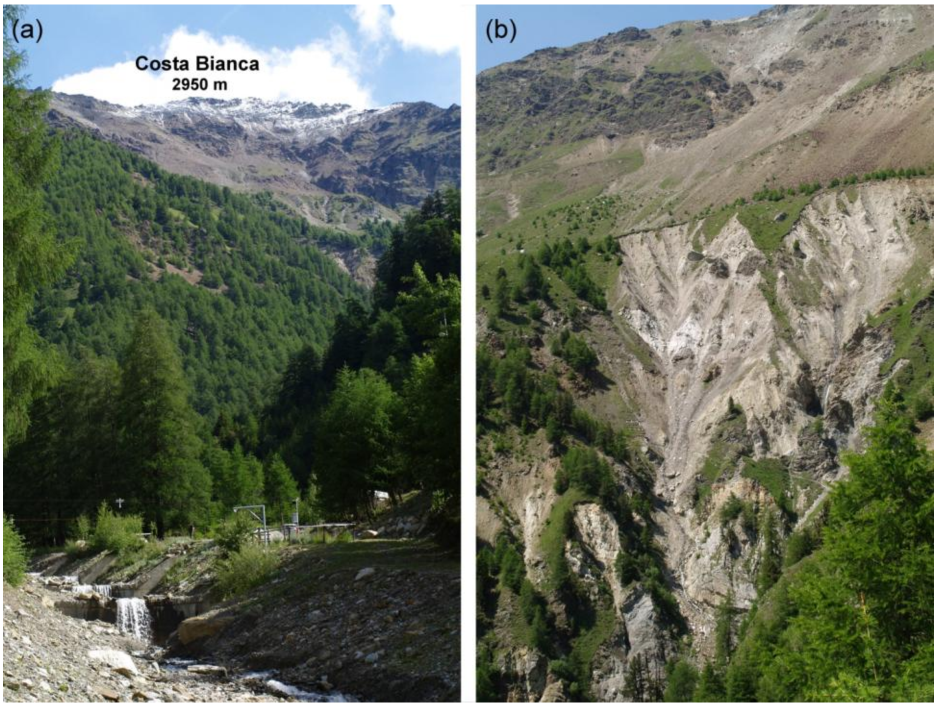

Figure 20 - (a) View from downstream to upstream of the Gadria basin, some monitoring equipment is visible along the torrent (i.e. stage sensors); (b) detail of a debris source area located along the Gadria channel in the Western upper basin (an elevation of about 2200 m a.s.l.).

4.2.4 The Gadria monitoring system

The station for monitoring debris flows and testing warning procedures was installed during spring 2011 at the confluence of the Gadria–Strimm channels (Figure 20a). The monitoring systems of the Gadria basin consists in rain gauges, radar sensors, geophones, video cameras, piezometers and soil moisture probes.

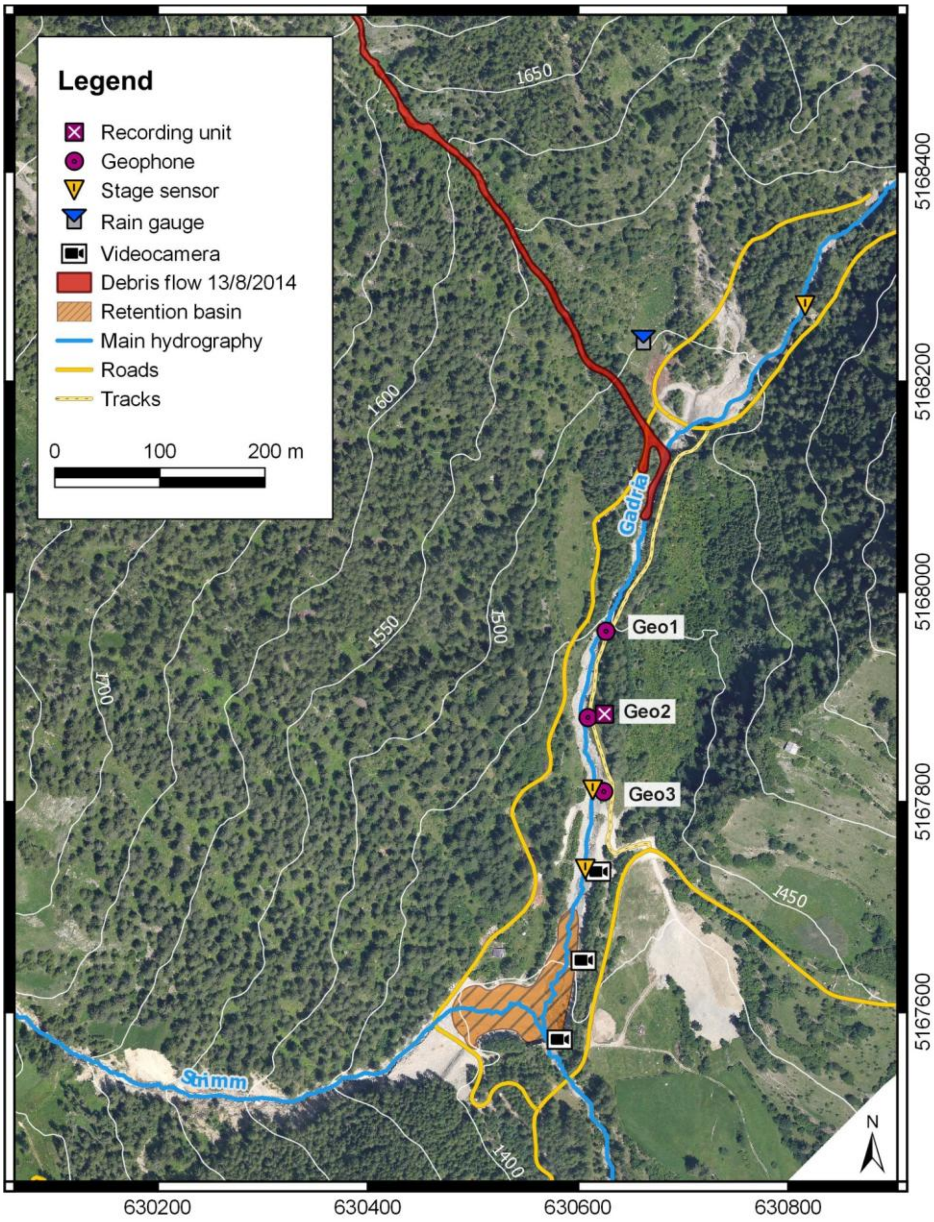

Figure 21 - Plan of the Gadria monitoring station, background image courtesy of Bolzano Province, coordinate system WGS 1984 UTM Zone 32N.

The sensors have been regularly installed and maintained since the spring of 2011. Most of the monitoring equipment was purchased and installed by the department of Hydraulic Engineering of the Autonomous Province of Bozen-Bolzano, with some instruments acquired and maintained by the Free University of Bozen-Bolzano and the CNR IRPI. The first geophones network was designed in 2011 and was composed by four vertical geophones installed at the same locations of the radar sensors in the Gadria channel. In 2012 the seismic equipment did not properly work and no data of the event occurred in august are available. In 2013, a new, stand-alone recording unit has been designed and set up in the Gadria torrent. In Figure 21 the plan of the seismic monitoring station equipped in 2013 is presented. The system is composed by three 10-Hz vertical geophone installed along the left bank of the torrent.

Considering the technical limitations of the monitoring equipment employed in the Marderello basin, a new monitoring equipment was designed to be installed in the Gadria basin. This new instrumentation was realized in the framework of the European Territorial Cooperation project Sedalp, which is devoted to provide a standardization of the data collection methods regarding sediment transport and debris flow monitoring (Arattano et al., 2015b). The new recording unit was also aimed to the development and test of warning algorithms based on the GVDs signal processing. A prototype, named ALMOND-F (Alarm and Monitoring System for Debris-Flow) was installed in 2013 in the Gadria basin. The ALMOND-F equipment is mainly devoted to the multi-parametric monitoring of debris flows, through the use of different sensors, and to the test of warning algorithms. The recording unit integrates eight programmable gains ranging from ±1V (gain = 1) to ±7mV (gain = 128) that permit to set the amplification level according to the distance of the sensor from the channel. ALMOND-F is based on the last version of SIAP+MICROS data logger and it has a storage capacity of 1Gb, large enough to cover a whole debris flow season.

4.3 Results

4.3.1 Torrential processes in the Marderello basin

In Figure 22 the Amplitude traces and the flow stage data are shown that were recorded on July 17, 2013 by the GVD network installed in the Marderello catchment. Only three seismic traces are shown because the geophone placed at station 4 was out of order. The waveforms that can be observed in Figure 22 are typical of debris flow phenomena. A sharp peak, corresponding to the passage of the main front in the vicinity of the sensor is present in each seismic trace. The peak is preceded by a sudden rise of the signal intensity that produces an abrupt ascending limb of the graph. The front is then followed by a gradual decrease of the signal intensity that requires some minutes to reach back a constant value. The latter is slightly higher than the background noise that preceded the arrival of the flow.

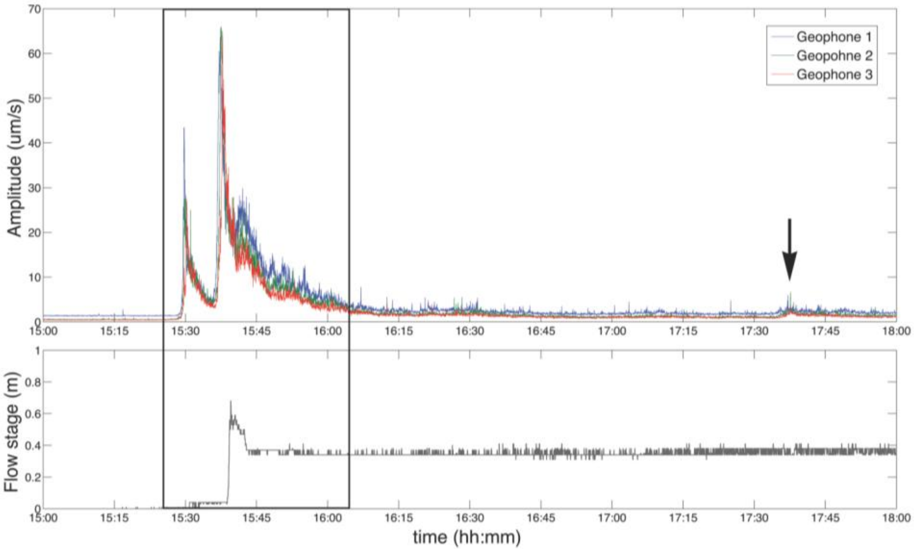

Figure 22 - Plot of the Amplitude versus time of the July 17, 2013 mud flow. The black frame contains the portion of the graphs enlarged in Figure 27. The arrow indicates a further waveform recorded about 2 hours after the passage of the main front.

The images recorded by the video cameras (Figure 23) allowed to recognize the nature of the flow process occurred in the channel, which was a mud flow of little dimension, preceded by a more liquid precursory wave. The hydrograph recorded by the stage sensor installed downstream the GVD network does not show the precursory wave, while the main front has a height of 60 cm. The mean front velocity of the two surges was calculated as the ratio of the distance between two consecutive sensors and the time interval between the first arrival of the signals at the two sensors; the application of cross-correlation techniques (Arattano and Marchi, 2005) allowed another estimation of these velocities (Table 4).

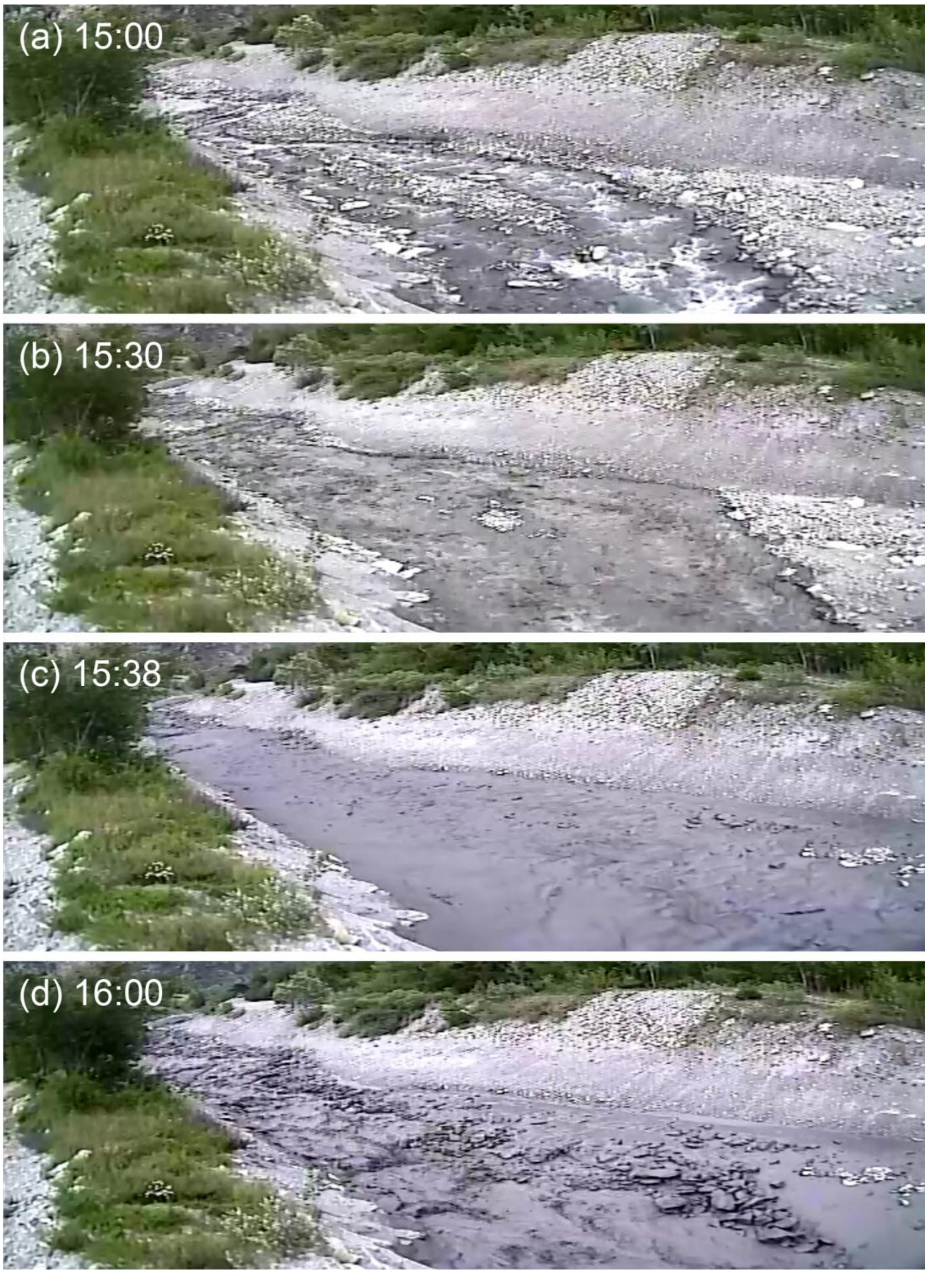

Figure 23 - Frames of the video recorded on July 17, 2013 by the video camera located along the road (see plan in Figure 18). In the first frame, the torrent in steady regime (h 15:00); in the second one the first surge (h 15:30); in the third frame, the mud flow front (15:38); in the last one, the tide (h 16:00).

Table 4 - The velocities of the events occurred on July 17, 2013 in the Marderello torrent. The velocities between the water fall and the geophone 1 have been estimated recognizing in the video the front overstepping the top of the water fall. Cross-correlation (CC) was applied to seismic data of the second surge.

Hyperconcentrated flow (first surge)

	Mean front velocity (m/s)
water fall - geophone 1	1.90
geophone 1 - geophone 2	3.40
geophone 2 - geophone 3	3.90

Mud flow (second surge)

	Mean front velocity (m/s)	Mean front velocity (m/s) with CC
water fall - geophone 1	1.00	-
geophone 1 - geophone 2	2.10	2.31
geophone 2 - geophone 3	2.50	2.45

On August 8, 2013 a small mud flow occurred in the Marderello torrent that was detected only by the GVDs network (Figure 24). The video cameras installed at Marderello, in fact, do not allow any recording after dark. No noticeable traces of the flow were identified in the torrent channel during the field survey carried out during the following days. The waveform visible from 21:40, with a positive time lag between the first arrival of the signal at the four sensors (Figure 24b), allows to ascribe the recordings to a torrential process. The process was probably a small and liquid mud flow. In fact, the phenomenon was not detected by the stage sensor and the maximum amplitude recorded was only slightly higher than 10 um/s (Figure 24). The time lag between the first arrival of the seismic wave at geophone 1 and geophone 4 is 32 seconds, which leads to estimate a flow velocity of 4.5 m/s. This value, confirmed applying the cross-correlation technique, is consistent with the velocity of the July 17, 2013 precursory surge. Furthermore, the maximum amplitude values reached by these two processes are similar, this confirms their nature of fast and small mud flow waves.

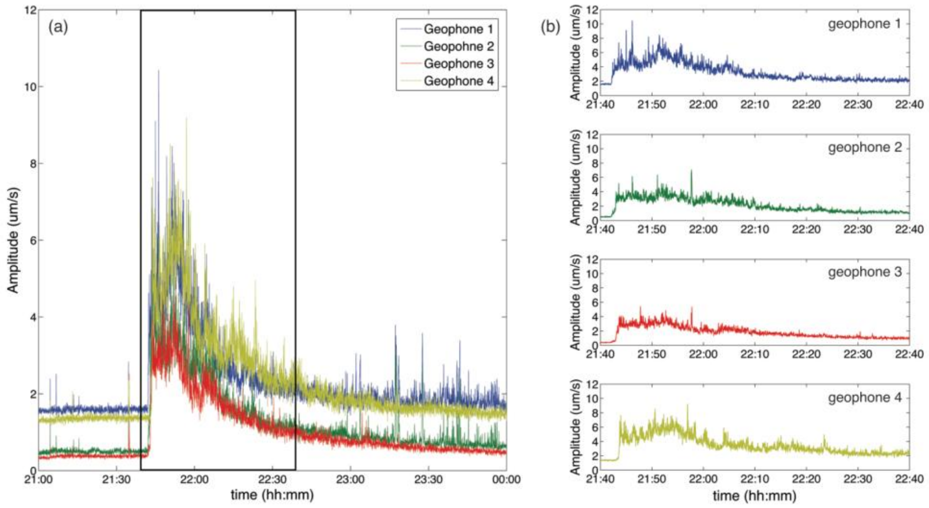

Figure 24 - Amplitude traces recorded on August 8, 2013 in the Marderello Torrent, the black frame in (a) contains the portions of the four Amplitude traces enlarged in (b).

4.3.2 Torrential processes in the Gadria basin

On July 8, 2014 a debris flood occurred in the Gadria basin that was detected by the monitoring system (Figure 25a). The signal is characterized by four long waves and the whole phenomenon lasted some hours. The signals recorded by the three GVDs have similar waveforms but different intensities. At 15:30 (local time) the Amplitude values recorded by the three geophones started rising from their background noise reaching, after one hour, values of 20 um/s at geophone 1, 10 um/s at geophone 2 and 5 um/s at geophone 3. The signal recorded by this latter sensor, in particular, presents several spikes that reach values higher than 10 um/s.

On August 13, 2014 a debris flow occurred in the Gadria basin, along a right tributary of the main channel, approximately at 14:00 (local time). This occurrence was reported by some hikers to the forest service of the Bolzano Province (Macconi, personal communication). The debris flow front did not get to the monitored reach of the torrent but entered the mail channel 200 m upstream geophone 1, stopping about 50 m beyond (Figure 21). The GVDs detected the signal shown in Figure 25a.

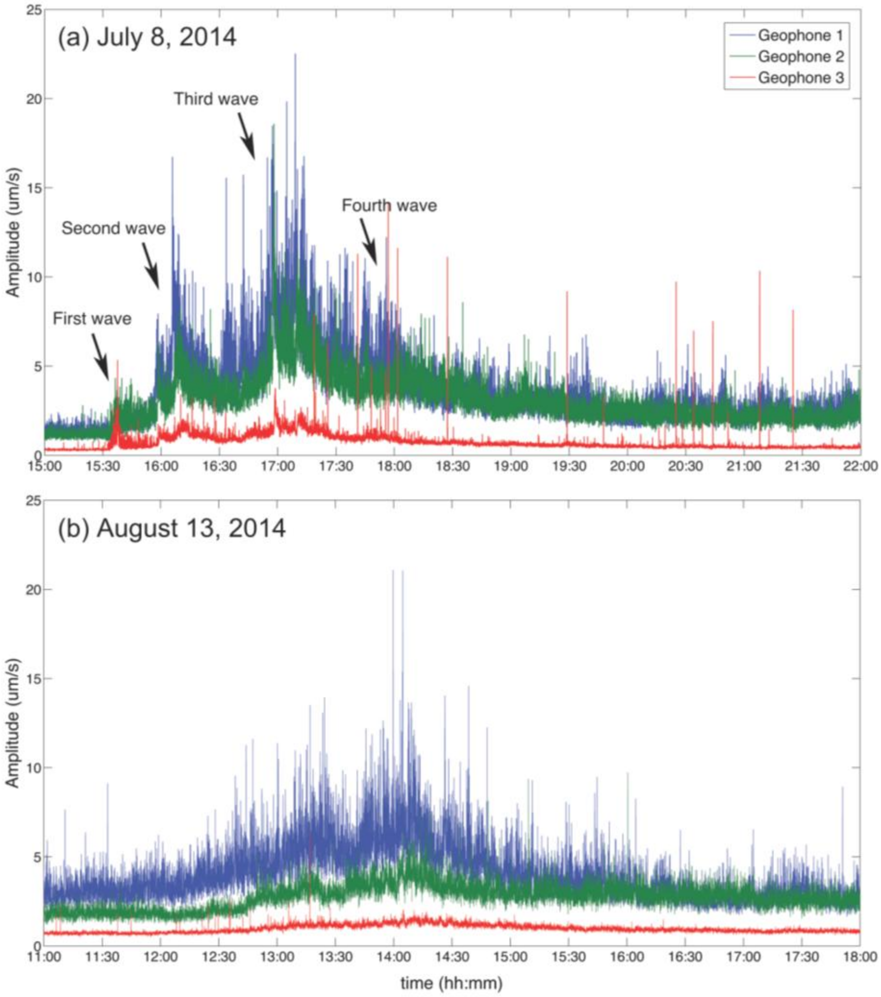

Figure 25 - The seismic recordings of the torrential processes occurred on July 8, 2014 (a) and August 13, 2014 (b) in the Gadria basin.

4.4 Discussion

A detailed analysis of the mud flow event that occurred on July 17, 2013 in the Marderello basin revealed that it was more complex than it appeared at a first sight. The presence of the high natural fall located about 300 m upstream of the GVD network (Figure 26) suggested to enlarge the seismic traces and inspect them in greater detail (Figure 27). The fall of the debris flow front from a significant height was in fact known to produce ground vibrations strong enough to be recorded by geophones placed at a distance of several hundred meters (Arattano, 2003).

In Figure 27c the enlargement of the graph is shown for geophones 1, 2 and 3. The signal from the first surge appears to be composed of two parts. The first part is a simultaneous peak that presents decreasing intensities in the three signals proceeding downstream (45 um/s on geophone 1; 28 um/s on geophone 2; 13 um/s on geophone 3). The second part is the actual precursory surge and has opposite characteristics: similar intensity at the three sensors (the peak is about 30 um/s) and a clear time lag between the first time arrivals at the three GVDs. These two parts are easily distinguishable in the signal recorded by geophone 3, while they partially overlap in the seismic trace recorded by geophone 1 (Figure 27c). The simultaneous peak is likely due to the impact of the mud flow front (the second surge) on the bottom of the water fall. After the fall, the mixture travelled with a mean velocity of 1 m/s. This value is consistent with the site topography, in fact the mixture is expected to flow very slowly in the almost flat retention basin located downstream the water fall (Figure 26). Downstream the check dam visible in Figure 26, the mixture accelerated reaching the velocity of 3 m/s in the monitored reach of the torrent. This value is consistent with the velocity estimations of previous mud flow events that occurred in the Marderello main channel (Turconi et al., 2008). The signal detected by geophone 3 also shows that the time lag between the simultaneous peak (15:29:46) and the first, precursory surge (15:30:18) is 32 seconds.

Figure 26 - The waterfall (100 m high) located 376 m upstream the station 1 of the Marderello monitoring station (a) and the monitored reach of the torrent located just downstream the waterfall (b). In these pictures taken on July 18, 2013 is possible to observe the traces of the mud flow that occurred the day before.

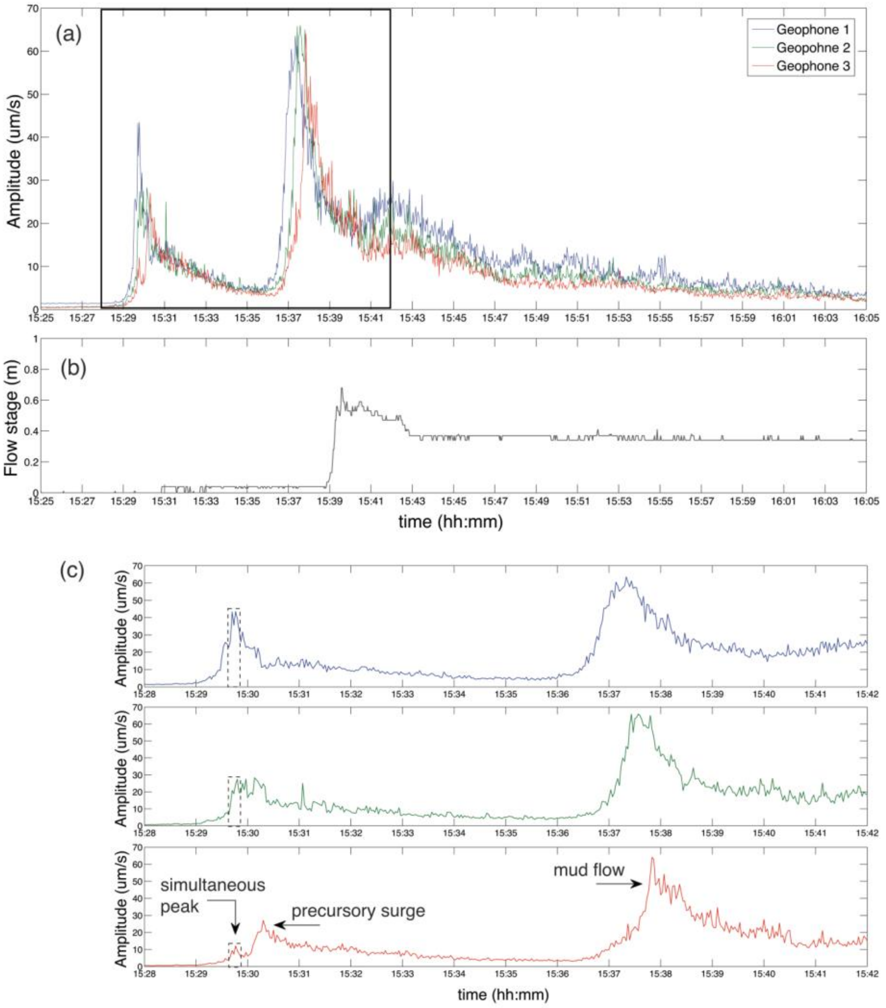

Figure 27 – Detail of the Amplitude (a) and the flow stage (b) versus time graphs of the July 17, 2013 mud flow that occurred in the Marderello basin. The black frame contains the seismic signals enlarged in (c) where the dashed lines emphasize the three simultaneous peaks recorded before the arrival of the two waves (precursory surge and mud flow).

This proves that the simultaneous peak cannot be ascribed to the impact of the precursory surge on the water fall bottom. Such surge should have travelled with a velocity of almost 15 m/s between the water fall and geophone 3 to reach the latter in 32 seconds. A velocity of almost 15 m/s is not consistent with the estimated velocities of the whole phenomenon (Table 4).

Table 5 - Distances (m) between the GVDs and the talweg at Marderello and Gadria. The detection distance is calculated taking into account the planar distance and the difference in altitude (perpendicular distance) between the sensor and the middle channel.

	Planar distance	Perpendicular distance	Detection distance
		Marderello	
Geophone 1	13.1	8.8	15.8
Geophone 2	18.1	8.5	20.0
Geophone 3	21.2	8.3	22.8
Geophone 4	11.5	5.5	12.8
		Gadria	
Geophone 1	7.7	3	8.3
Geophone 2	5.2	2.5	5.8
Geophone 3	10.5	2.8	10.9

The superposition of a simultaneous signal with the precursory surge of the mud flow is not the only one interesting characteristic of this signal. The graph of Figure 22 shows a further, small surge occurring about 2 hours after the passage of the main front of the mud flow occurred on July 17, 2013 in the Marderello basin. This small surge appears as a very small wave (maximum amplitude of 7 um/s) of brief duration (5 minutes) recorded by all GVDs along the Marderello Torrent. This occurrence was neither detected by the stage sensor nor visible in the recordings of the Marderello monitoring system, as a consequence it aroused our curiosity and induced us to better investigate its origin.

Even though no wave was present in the video, the characteristic form of the seismic recording occurred at 17:35 suggested that the signal might have been produced by a torrential process. This possibility led us to investigate the torrent beds of the basins surrounding the Marderello catchment to see if they had been affected by any torrential process or slope instability along the banks. Indeed, we discovered that on July 17, 2013 a debris flow event also occurred in the Malo Torrent, a close tributary of the Cenischia stream (Figure 16). A picture of the Malo debris flow front arrival, with the time of occurrence, has in fact been taken by an inhabitant of the village of Novalesa (Figure 28). In the picture he took at 17:48, a powder cloud due to the front passage is barely visible under the “three arches bridge” and the flow of a precursory surge is already observed along in the torrent bed (Figure 28a). The debris flow then propagated along the entire channel and reached the Cenischia stream (Figure 28b,c,d) leaving remarkable tracks in the channel bed (Figure 29).

Figure 28 - Frames of the video recording made by an inhabitant of the village of Novalesa along the Malo torrent, few meters upstream the confluence with the Cenischia stream, on July 17, 2013. All view are from downstream to upstream: (a) the channel bed few minutes before the arrival of the main front; (b) the debris flow boulder front; (c) a secondary liquid surge; (d) the muddy tail of the phenomenon.

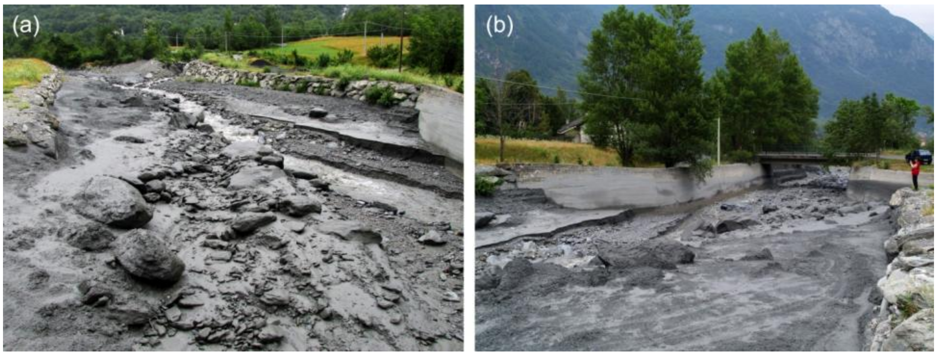

Figure 29 - Detail of the Malo torrent channel bed the day after the debris flow: (a) deposits in the channel bed, photo taken from downstream to upstream; (b) deposits in the channel bed and traces of the passage of the flow on the bridge abutments, view from upstream to downstream (photos taken in the same location where the frames presented in Figure 28 were shot).

Therefore, we interpret that the recording at 17:35 (Figure 22) was produced by the debris flow event occurred in the Malo torrent. However it remains to be clarified which moment of the debris flow propagation along the Malo torrent had been captured by the Marderello microseismic network. If the debris flow had propagated along the entire Malo torrent, it had to be established when and where it produced the recordings observed in the graph of Figure 22. The signal in fact only lasts 5 minutes and thus it could have been produced by the interaction of the debris flow with a specific morphological feature (i.e. a bend of the torrent, the jump from a check dam) that produced an increase of ground vibration intensity. The recordings might have been also produced by the passage of the debris flow along the reach of the Cenischia stream that is closest to the Marderello monitoring station.

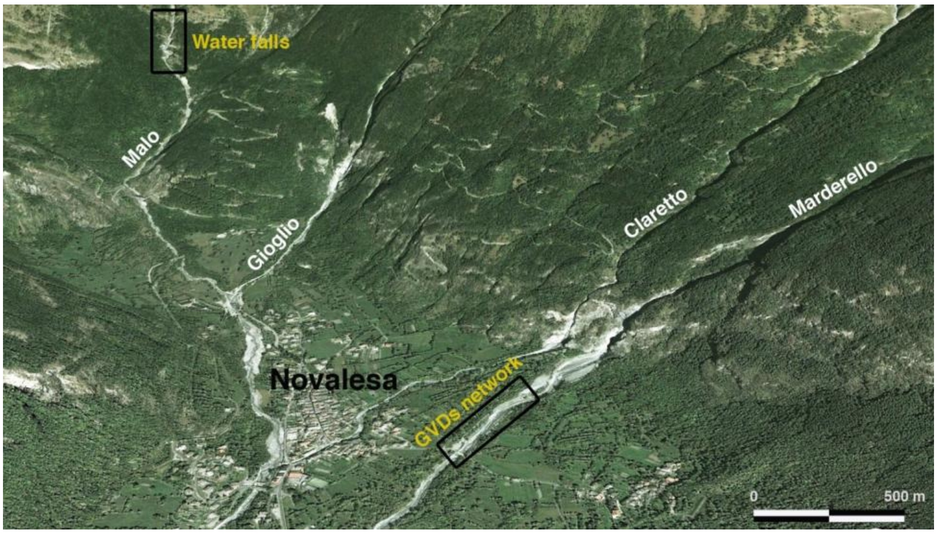

Figure 30 - Aerial view of the left Cenischia valley, background image ©2014 DigitalGlobe. The frames indicates the position of the Malo water falls and of the Marderello GVDs network.

The most significant morphological feature that is present in the Malo torrent, apart from some bends of the channel distributed along its path, is a natural fall, 100 m height, located at a distance of 2 km from the microseismic network (Figure 30). This is probably the origin of the recordings visible at 17:35. The fall from a natural or artificial fall has already shown to be capable of producing vibrations that can be recorded at a great distance (Arattano, 2003). On the contrary a distance of 1-2 km without any natural fall or obstacle, as that separating the network from the closest Malo reach, is too large for producing ground vibrations detectable, since their intensity decays exponentially with distance (Abancó et al., 2014). Another possible origin of the signal could be found in the upper part of the Marderello torrent, characterized by a succession of canyons and waterfalls, but this area is farther away from the GVDs network than the Malo water fall. A confirmation of the hypothesis that the investigated small surge was due to some process that occurred at significant distance also came from the application of the cross-correlation analysis. This led to the estimation of a time lag equal to zero among the signals recorded by the different geophones. Consequently, being simultaneous on the three sensors, this signal cannot have been generated by a torrential process that occurred in the monitored reach of the Marderello torrent.

In Figure 31 the ground vibration data recorded by geophone 3 in the Gadria basin on July 8, 2014 are presented, together with a selection of images shot by the video camera that frames the cross section where this sensor is installed. In this figure is possible to appreciate the correspondence between the different phases of the phenomenon evolution and the related seismic signal. Moreover, geophone 3 is the sensor located at a distance from the channel bed that permits to better appreciate the waveform corresponding to a low-intensity process such as a debris flood. Between 15:25 and 15:35 the first wave of the debris flood flowed in the channel (Figure 31a,b) and the Amplitude values recorded by geophone 3 raised from their medium background noise to a value of 5 um/s.

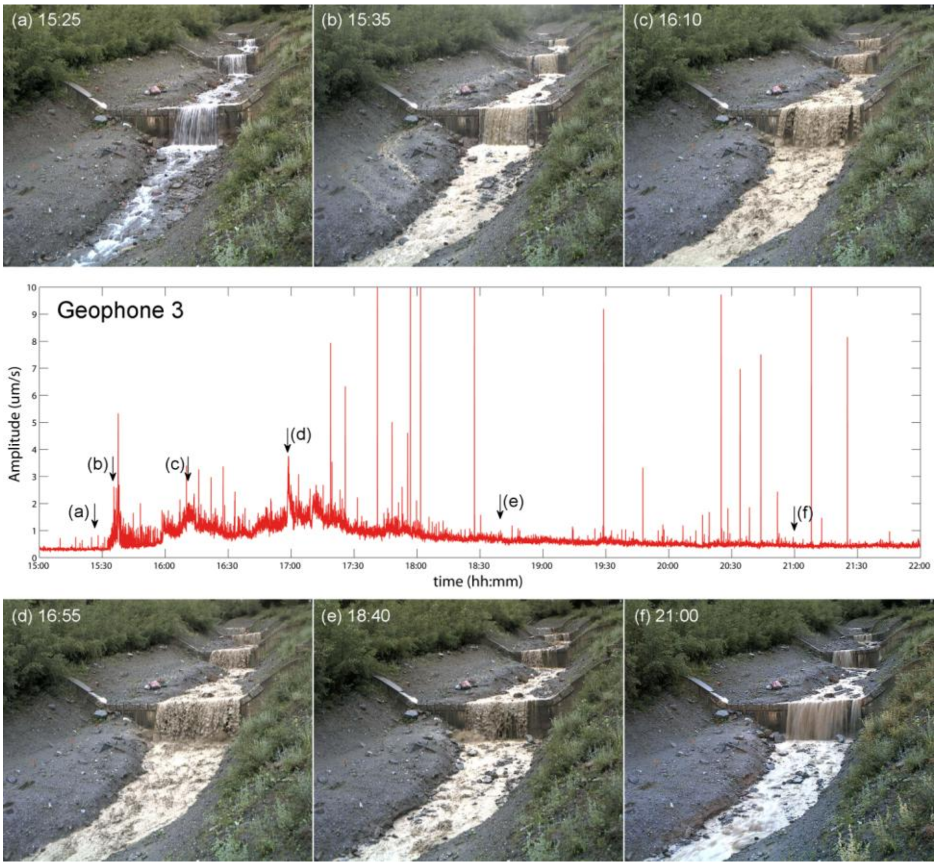

Figure 31 - Amplitude recorded by geophone 3 in the Gadria basin on July 8, 2014 together with a selection of frames shot by the video camera located downstream the sensor.

Afterwards this first debris flood wave three other surges followed (Figure 31 c,d,e) that were already identified in Figure 25. The debris flood event approximately ended at 21 o'clock (Figure 31e) and lasted around 4 hours on the whole. The flow discharge qualitatively estimable from the images seems to be consistent with the different ground vibration intensities observed in the seismic trace. However, it has also to be noticed that if the distance between the geophones and the torrent bed plays a significant role, sometimes it also makes complicate the understanding of the main signal sources. In fact, the background noise values recorded by the GVDs on August 13, 2014 between 10 and 11 o'clock are, again, inversely correlated with the distance sensor-talweg (Table 5). However, their intensities are slightly different from the previous case.

Focusing debris flow event occurred on August 13, 2014, tracks of the passage of the flow were observed along the tributary of the Gadria torrent that produced the event (Figure 32a). In correspondence of the intersection between the channel and the pedestrian track, the debris flow separated in two lobes, one reached the main channel and the other one stopped few meters beyond (Figure 21). The front did not get to the monitored reach of the torrent and the coarse particles transported by the flow stopped in the main channel around 150 m upstream station 1 (Figure 32b). The main source of vibration should have been the impact of the material transported by the flow with the left bank of the main channel. This would be consistent with the fact that the intensity of the signal recorded by the GVDs network decreases with the distance from the source. Geophone 1, the sensor located closer to the area interested by this process, recorded the higher amplitude, while geophone 3 registered the lowest values of ground vibration (Figure 25). This could be in agreement with the observations made in the Marderello basin. However, the maximum ground vibration amplitude recorded are very similar to those reached in the Gadria basin during the debris flood event of July 8, 2014. This leads us to cross-check GVDs data with the images from the video monitoring system. We found that during all day the Gadria torrent was also affected by a flow with a significant bed load transport that could have had an impact on the seismic signal. No particular debris flood waves were observed in the signal, but the duration of the whole phenomenon (4 hours, from 12 to 16 o'clock) lead us to interpret this signal as the result of the overlapping of different processes.

It has also to be noticed that, again, the distance between the geophones and the torrent bed could play a significant role, making complicate the understanding of the main signal sources. The background noise values recorded by the sensors and recognizable between 10 and 11 o'clock are inversely correlated with the distance sensor-talweg. Indeed, the higher background noise recorded by the three geophones before 12 o'clock, can be ascribed to the bed load transport. This process had an increasing intensity that reached its maximum intensity in correspondence to the activation of the debris flow along a tributary of the Gadria torrent. In this context, the exact portion of the signal produced by the debris flow is hard to identify.

Figure 32 - Traces of the passage of the debris flow occurred on August 13, 2014 along a right tributary of the Gadria main channel: (a) erosion in the intermediate section of the channel; (b) deposits at the junction with the main channel (images courtesy of Pierpaolo Macconi).

4.5 Conclusions

Debris flows and mud flows are natural processes that may cause severe damage to human settlements and infrastructure. Monitoring these phenomena in instrumented catchments allows the collection of field data that can provide fundamental information for research purposes. The monitoring data and the inferred quantification of the transported sediment are also important for hazard assessment, land-use planning, and design of torrent control structures, including warning systems. Classical monitoring devices (stage sensors, video cameras, wire sensors) need to be placed above or at least very close to the torrent where debris flows propagate. On the contrary, GVDs offer the possibility to be installed outside of the channel bed and this greatly diminishes the possibility to be damaged by an event, which is particularly important if GVDs are being used as warning devices. For the same reason, they can be adapted more easily to the different and often difficult environmental conditions that are found in the field.

Seismic signals alone do not always allow a complete characterization of torrential processes. This is particularly true when the GVDs network is installed in complex morphological settings. In the Marderello basin, without data from the videocamera and the stage measurements, we would have not been able, probably, to correctly interpret the nature of the different recorded events. A consistent interpretation of the GVDs data was also reached reconstructing the event dynamics through other monitoring data and field observations made in the basins nearby. On the contrary, a correct interpretation of the monitoring data gathered in the Gadria basin was obtained proceeding in the opposite way. Starting from the event documentation, the event dynamics was inferred through the interpretation of GVDs monitoring data.

The use of GVDs for warning purposes requires caution and experience because they may detect different torrential processes besides debris flows and mud flows. Some examples have been provided in this paper, derived from both the Marderello and the Gadria instrumented catchments. Moreover, a GVD network may detect other phenomena occurring outside the monitored basin. Such distant processes, however, usually produce simultaneous responses at GVDs installed at different cross sections along the torrent. These signals can be therefore easily recognized without spreading any alarm. Geomorphologic discontinuities (high waterfalls or check dams) located in the monitored basin or in basins nearby, might also cause seismic recordings that can be distinguished from those produced by the passage of a debris flow. The drop of the debris flow front from a water fall can be detected from a distance using GVDs. Again, this would produce simultaneous peaks in the seismic signal that can be recognized. All the data herein presented can be useful to develop reliable warning algorithms and to reduce the occurrence of false alarms. However, in general more instruments than a GVDs array alone would be needed to grant an effective warning.

The seismic datasets gathered in the Marderello and Gadria basins have also revealed the possibility to effectively monitor bed load transport with a GVD array installed outside the channel. The seasonal datasets gathered in the two basins will be thoroughly analyzed to identify further bed load transport events and to better investigate this issue. Sediment-water flows occurring in mountain torrents may show a variety of regimes, ranging from water flows with low bed load transport to massive transport of debris. Sometimes field surveys may allow the reconstruction of the development of these processes in time, but the possibility to infer this information from GVDs data detected outside the channel would provide an interesting new source of investigation that may lead to interesting practical applications.

5 Methods of data processing for debris flow seismic warning

5.1 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 (Badoux et al., 2008; Berti et al., 2000; Chou et al., 2010; Marchi et al., 2002; Navratil et al., 2013; Turconi 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 (Arattano et al., 2006; Coussot et al., 1998; Iverson, 1997), 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. 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 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.

5.2 Why warning algorithms based on seismic data?

Seismic devices have already been proposed and employed as warning sensors (Abancó et al., 2014; Badoux et al., 2008). 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 (Arattano et al., 2015b).

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 (Abancó et al., 2014; Badoux et al., 2008). 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 33 clearly shows an important advantage that ground vibration detectors have, in comparison with stage sensors. Fig. 1b 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 (Figure 33c). 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 Figure 33 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 (Figure 43).

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 et al., 2014). It clearly emerges from Figure 33 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 might 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.

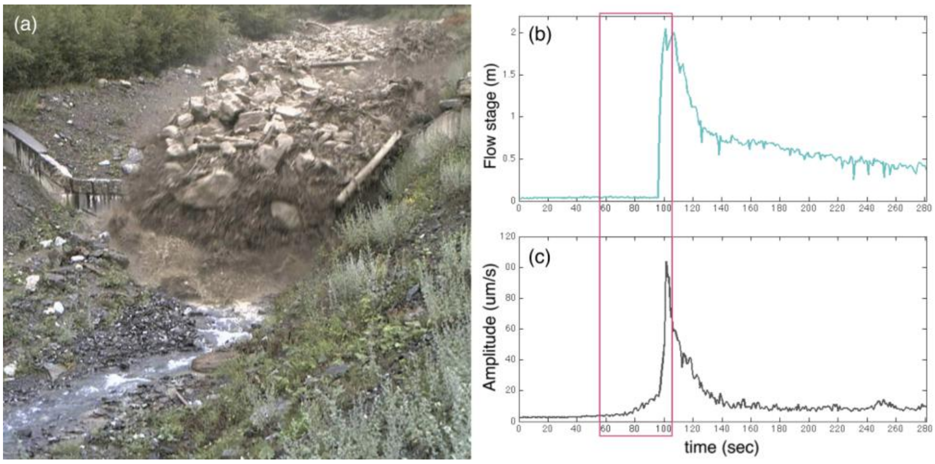

Figure 33 - Debris flow occurred in the Gadria basin (Northeastern Italian Alps) on July 18, 2013: (a) arrival of the main front, (b) hydrograph and (c) Amplitude graph. In the Amplitude graph the detection of the debris flow arrival occurs more than 20 seconds before the curve reaches of the peak.

5.3 Effects of data processing on debris flows detection

5.3.1 Direct impact of the processing methods

In Figure 34 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 Figure 34 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 Figure 34. These aspects had already been noted by (Arattano et al., 2014). However, examining Figure 34 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.

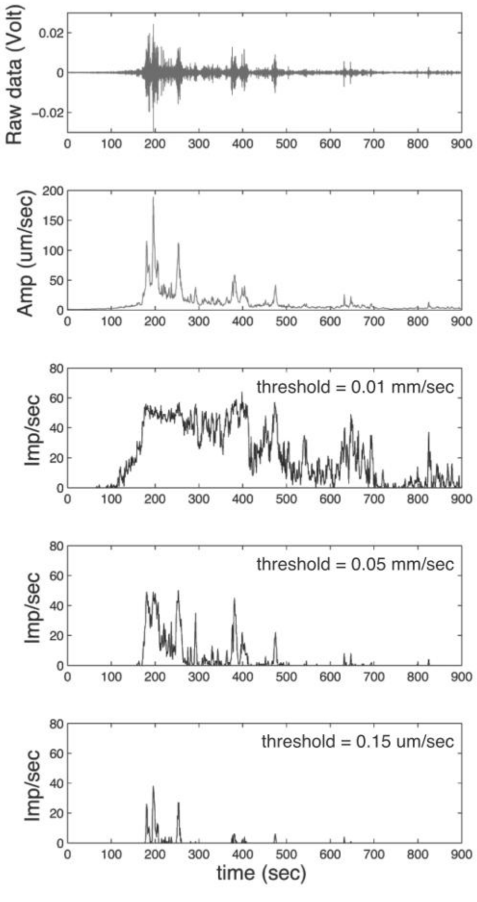

Figure 34 - The raw data (sampling rate = 250 Hz) recorded by a vertical geophone (first row), the Amplitude graph (second row) and three Impulses curves produced applying different threshold values of the debris-flow event occurred in the Rebaixader basin on July 4, 2012.

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.

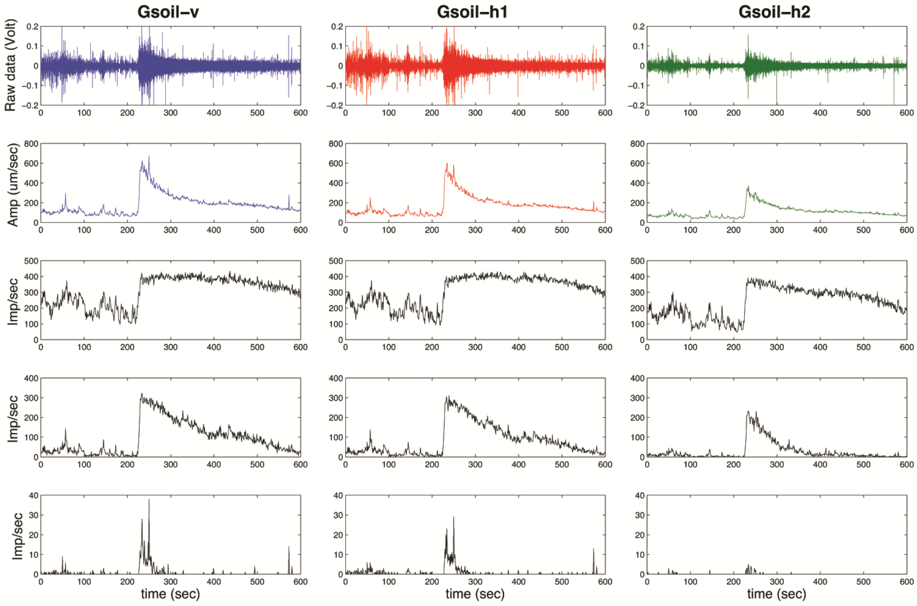

Figure 35 - First row: raw data (sampling rate = 2000 Hz) recorded by a triaxial geophone installed in the ground in the Illgraben basin for a debris-flow event occurred on July 27, 2009; second row: graph of the Amplitude; following rows: three curves of the impulses produced applying different threshold values (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).

From the analysis of Figure 34 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 Figure 35 seem to show that this is not always the case. In Figure 35 the ground vibration data are shown that were recorded along the three axes 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 the data of Figure 34 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 comparing the raw data shown in the first row of Figure 35 with those shown in the first row of Figure 34. 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 Figure 35).

5.3.2 Effects of the sampling frequency

Another aspect that might 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 Figure 36 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.

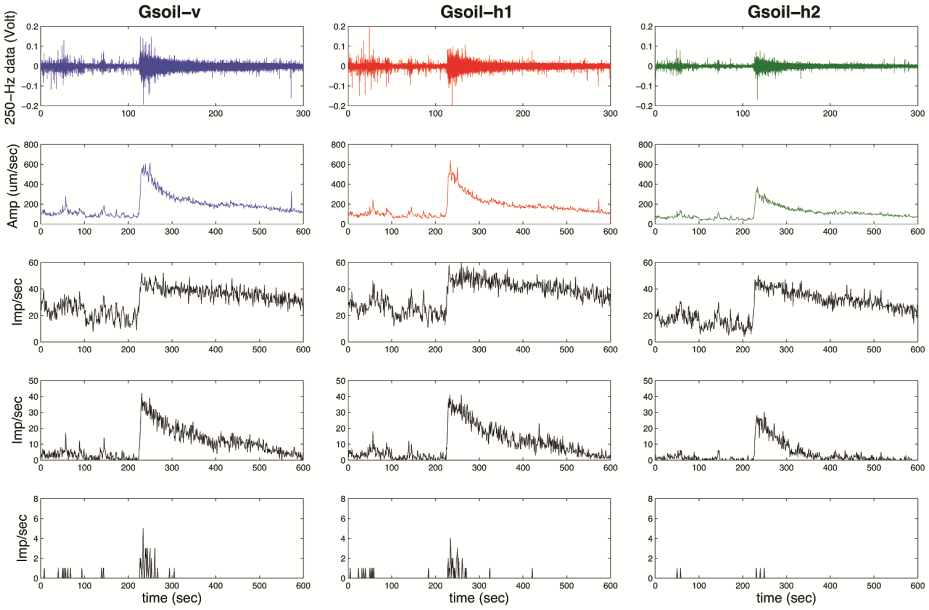

Figure 36 - Data from the debris-flow event occurred on July 27, 2009 in the Illgraben basin after a sub-sampling at 250 Hz.

The main reasons why the 250-Hz signal produces such a decrease of the number of impulses compared to the 2-kHz one appears to be the cut of the high frequencies generated by the sub-sampling (Figure 37). In this figure, two seconds of seismic recordings extracted from the 2-kHz and from the 250-Hz signals are enlarged. The amplitude spectra have been calculated on two time windows, both on the signals sampled at 2 kHz and on the signals sub-sampled 250 Hz. In the first case, the main frequency values range in the interval of 200-300 Hz for the first time window (w_1) while a main frequency of 20 Hz dominates the second time window (w_2). Calculating the frequency spectra but on the signal sub-sampled at 250 Hz on the same time windows, in the first case (w_3) all the information on frequency is lost but in the second case (w_4) the main frequency of 20 Hz is still visible.

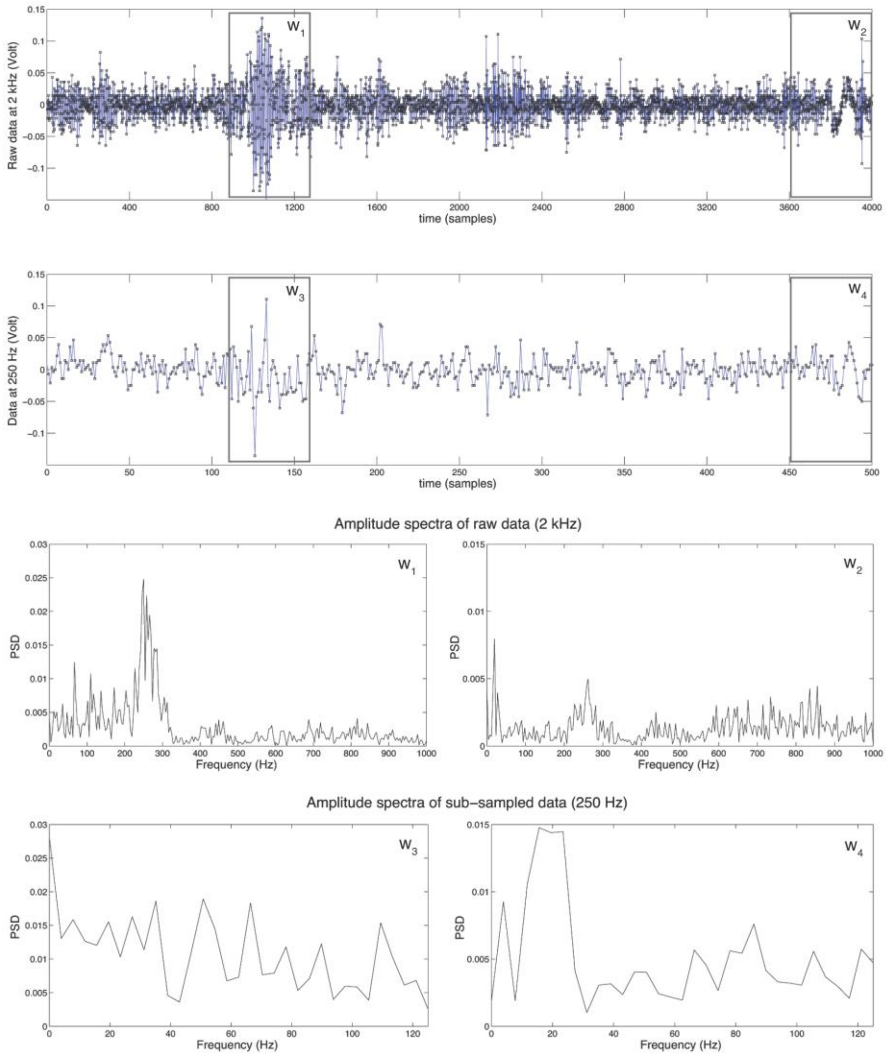

Figure 37 - Above, two seconds of recording (channel Gsoil-v) of the debris flow occurred on July 27, 2009 in the Illgraben basin: raw data (sampled at 2 kHz) and sub-sampled data at 250 Hz. Below, the amplitude spectra of two time windows per trace, extracted both from the 2-kHz signal (w_1 and w_2) and from the 250-Hz signal (w_3 and w_4).

5.3.3 Damping effect of channel sediment cover

In this section, the first debris flows seismic recordings gathered in the Chalk Cliffs instrumented basin (Figure 38), central Colorado (USA), are presented. In May 2014, we installed two 4.5-Hz, three-axial geophones in the upper part of the catchment (upper station, Figure 39). Seismic data are sampled at 333 Hz and then recorded by a standalone recording unit. One geophone was directly installed on bedrock, the other one mounted on a 1-m boulder partially buried in colluvium. This latter sensor integrates a heavily instrumented cross-section consisting of a 225 cm^2 force plate recording basal impact forces at 333 Hz, a laser distance meter recording flow stage over the plate at 10 Hz, and a high definition video camera (24 frames per seconds).

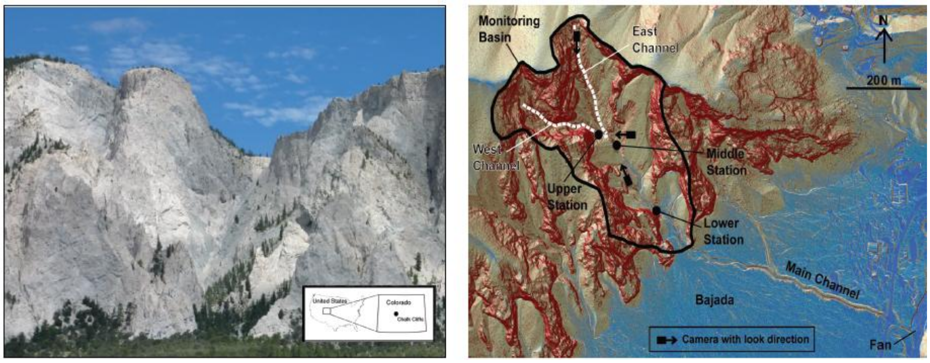

Figure 38 - Location and simplified map of Chalk Cliffs basin, CO (USA). Modified after (Kean et al., 2014).

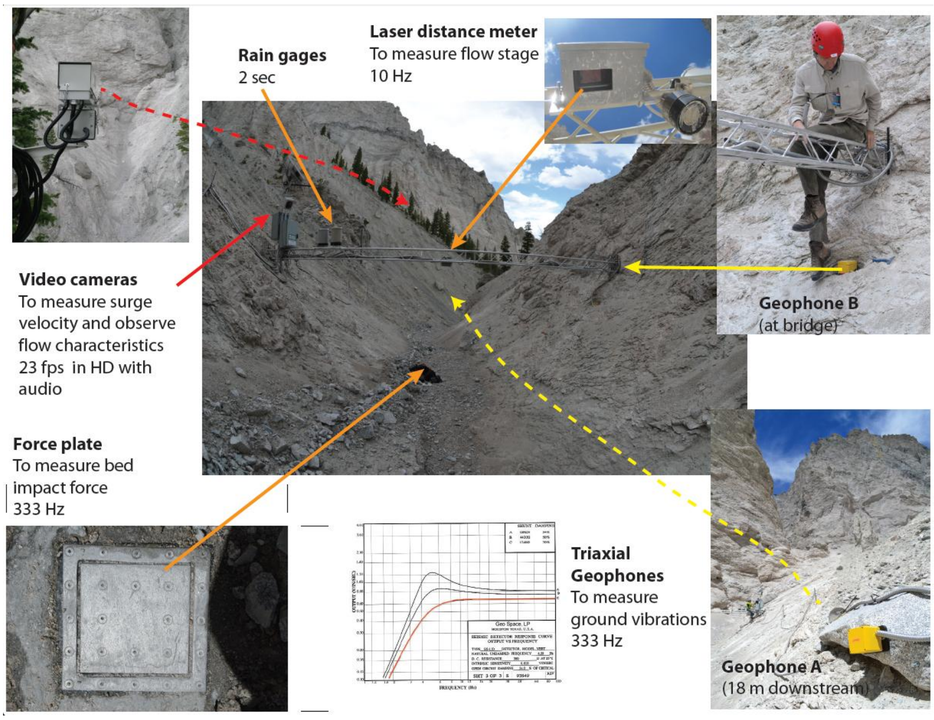

Figure 39 - The heavily instrumented upper station of Chalk Cliffs monitoring station (Kean et al., 2014).

This combination of instrumentation allows for a comparison of the amplitude and spectral response of the geophones to flow depth, impact force, and video recordings. On July 4, 2014 a debris flow event occurred in the basin that was recorded by the whole monitoring system. Both geophone installation methods and channel bed characteristics largely influenced the seismic records. One geophone exhibits a broad frequency response during all debris flow surges (Figure 41), while the energy recorded by the other one is mainly concentrated in the 40-80 Hz band (Figure 40). As already observed at Gadria (Figure 5), the geophone installation methods have an impact on the recorded seismic signal, both in amplitude and in frequency domains. Geophone A, mounted on a 1-m boulder partially buried in colluviums, significantly damps the high frequencies. Thus, the spectrogram presents a classical debris flow seismic signatures, with 20 < f < 100 Hz. Furthermore, small rock falls also play a role on Geophone A spectrogram shape, see the precursory seismic activity recorded before the arrival of the first surge (Figure 40).

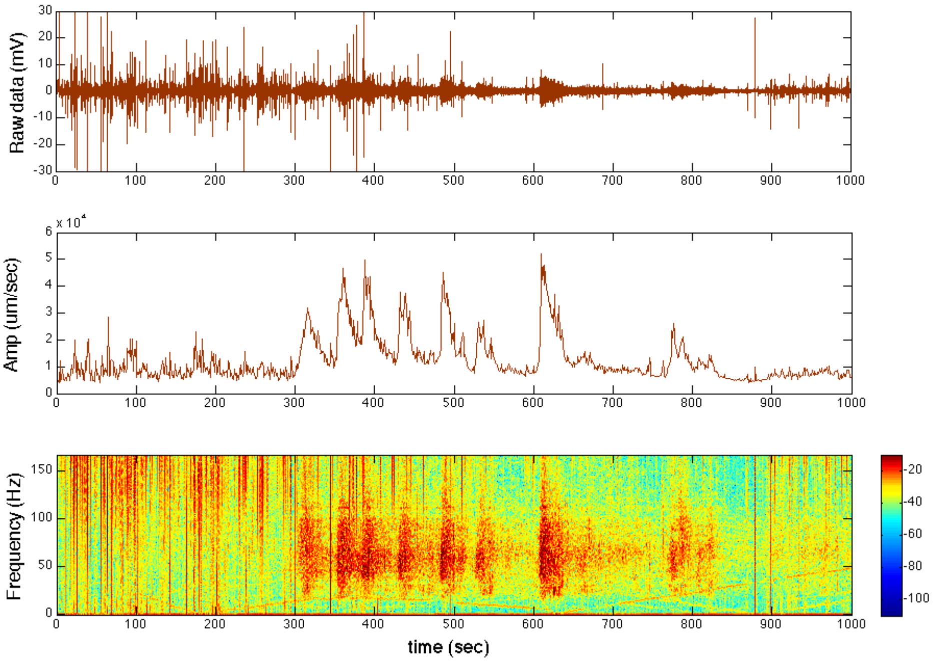

Figure 40 - Debris flow occurred on July 4, 2014 at Chalk Cliffs: data from geophone A (mounted on a 1-m boulder partially buried in colluvium).

Erosion and entrainment processes also have a crucial effect on the recorded waveforms. The presence of channel bed sediment damps the Amplitude waveforms during the first four surges, when the flow is not yet erosive. The typical proportionality between the Amplitude curve and the flow stage is observed only after the entrainment of the channel bed sediment by the debris flow, starting from the fifth surge, when the flow is directly on bedrock (Figure 41).

The processing of the signal with the Impulse transformation displays the same damping effect observed on the Amplitude curves when a high threshold is adopted. However, the use of a high threshold entails the disappearance of the first surge and causes a less effective early detection of the flow. On the contrary, the adoption of a lower threshold impedes the observation of the sediment damping effect (Figure 42).

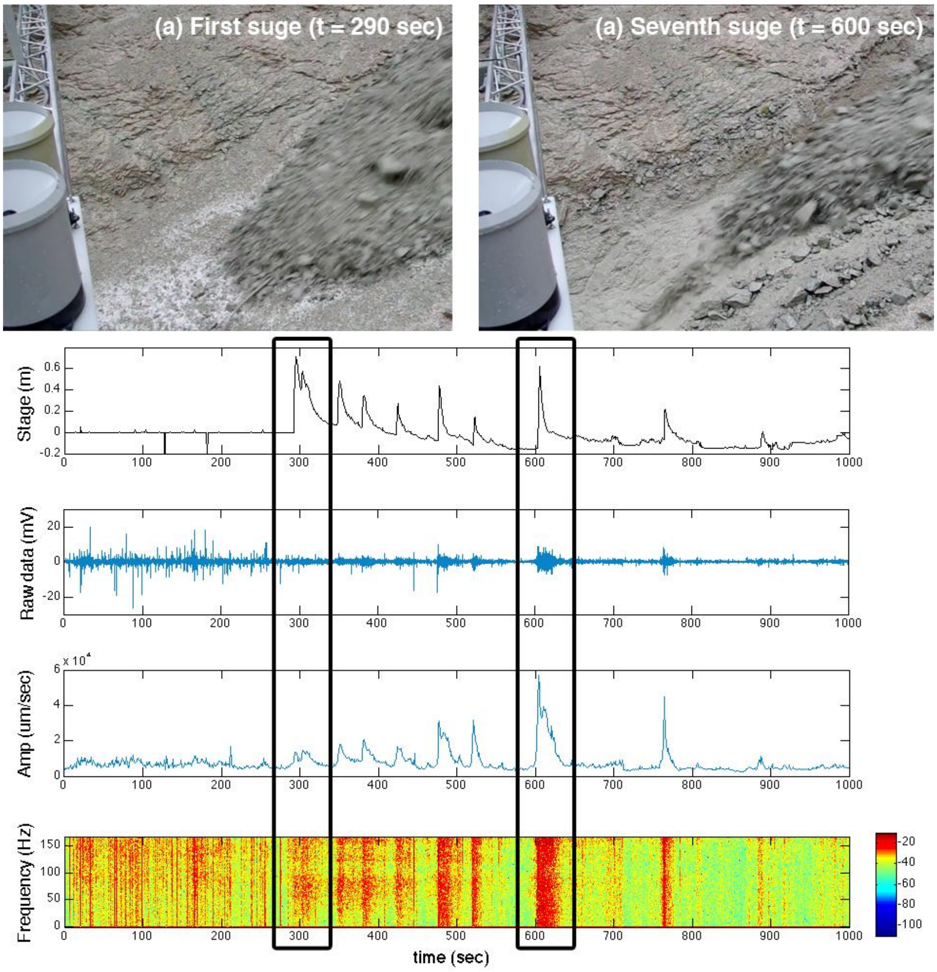

Figure 41 - Debris flow occurred on July 4, 2014 at Chalk Cliffs: data from stage sensor, geophone B (installed on bedrock) and frames from the first and the seventh surges.

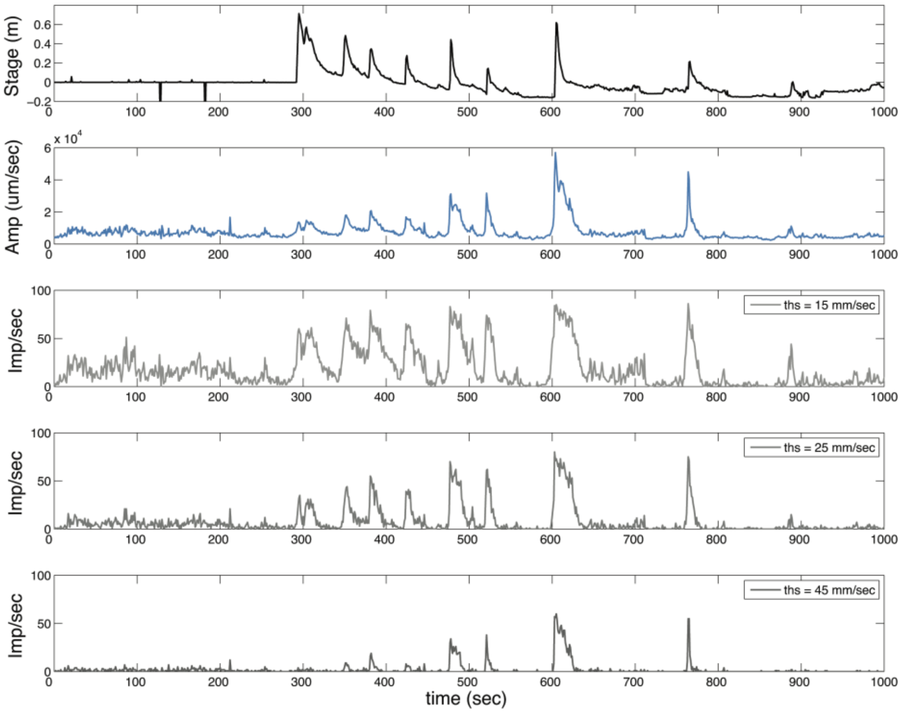

Figure 42 - Debris flow occurred on July 4, 2014 at Chalk Cliffs: data from stage sensor and geophone B (installed on bedrock) transformed in Amplitude and Impulses.

5.4 Conclusions

Both method of Amplitude and method of Impulses are suitable for debris flow early detection. The effects of the use of the different data processing methods on debris flow early detection are hereinafter summarized: (i) the Amplitude waveforms do not show any particular modification changing the sampling frequency of the raw signal while the Impulses curves do; (ii) any particular insights of the Amplitude methodology affect the capabilities of debris flow early detection, on the contrary, the choice of the threshold in the Impulses methodology does; (iii) applying the method of Impulses, a too low threshold might provide few information on the debris flow generation and evolution since it may result in a flat graph; (iv) with a higher threshold, the shape of the debris flow surges are better performed, however, the rise of the impulses curve starts much later than using lower thresholds and therefore the early detection is less effective; (v) in case of channel bed sediment cover, the typical proportionality between the Amplitude curve and the flow stage is observed after the entrainment of the channel bed sediment by the debris flow, while a non-optimal the choice of the Impulses threshold impedes the observation of the sediment damping effect; (vi) the use of the method of impulses for warning purposes would conflict with its use for monitoring: separate thresholds should be adopted.

6 Algorithm for debris flow early warning based on ground vibration monitoring

6.1 Introduction

In the Alpine region, debris flows cause extensive damage and several casualties every year (Guzzetti et al., 2005; Hilker et al., 2009). Construction of residential buildings and transport infrastructures on debris-flow fans has progressively increased the vulnerability to such events, thus augmenting the overall risk (Comiti et al., 2014). In this context, today the key points in the field of risk management are the capability to forecast debris flow phenomena and the level of preparedness of populations highly exposed to natural hazards. For this reason, long-term instrumental observations of debris flows (e.g. Marchi et al., 2002; Suwa et al., 2011) are carried out both for research and decision-making purposes. Monitoring can provide essential data for debris flow modeling (Arattano et al., 2006), the understanding of initiation conditions (Coe et al., 2008) and the study of sediment connectivity (Cavalli et al., 2013). Furthermore, monitoring data can also supply precious information for hazard assessment, land-use planning and designing torrent control structures and/or warning systems.

Different types of devices are used to monitor debris flow processes (Itakura et al., 2005), but ground vibration detectors (GVDs) present a number of significant advantages: (i) they can be installed outside the channel bed, (ii) they are highly adaptable, even to harsh field conditions, and (iii) they can detect the debris flow front arrival early. As a consequence, in recent years the adoption of GVD as monitoring tools for debris flows is worldwide increasing (Arattano and Marchi, 2008; Bessason et al., 2007; Chou et al., 2010; Cui et al., 2005; Fang et al., 2011; Huang et al., 2007; Kogelnig et al., 2011; Navratil et al., 2013; Suwa et al., 2000).

The installation of a GVD array at a proper distance from the torrent bed may allow the estimation of important parameters such as the velocity of the main debris flow surges and their volume. However, GVDs may detect other flow processes like debris floods and hyper-concentrated flows, but also slope failures, even those occurring far away from the monitored torrent reach (Abancó et al., 2014; Coviello et al., 2015a; Hürlimann et al., 2012). All this information has to be taken into account when the monitoring is performed for warning purposes.

A growing number of studies investigate the reliability of landslide EWSs, their comparability to alternative protection measures and their cost-effectiveness (Cloutier et al., 2014; Michoud et al., 2013; Sorensen, 2000; Stähli et al., 2014). EWSs from debris flows can be classified into two main types: advance and event EWSs

(Arattano and Marchi, 2008). Advance EWSs predict the possible occurrence of a debris flow by monitoring hydro-meteorological processes that may lead to initiation conditions, typically rainfall. This kind of EWS has been deployed since the 1970s in the USA (Keefer et al., 1987) and nowadays it is widely adopted (Aleotti, 2004; Baum and Godt, 2009; Jakob et al., 2011). Despite their widespread adoption, these latter systems are prone to false alarms because they are heavily affected by uncertainties in precipitation forecasts and in the estimates of local threshold curves.

Event EWSs are based on the detection of debris flows when the processes are in progress. They have a much smaller lead time than advance warning systems and their effectiveness strictly depends on the possibility (i) to perform accurate and rapid measurements, (ii) to automatically process, store and validate monitoring data, and (iii) to promptly disseminate the obtained information spreading an alarm. An event EWS for debris flows is based on measurements from wire sensors, ground vibration sensors or stage meters, upstream of a precisely defined vulnerable site. They can be particularly effective in the protection of all those vulnerable infrastructures (such as railways and roads) that do not require an excessively long alert time. Owing to these characteristics, event EWSs are potentially highly reliable, even though the need of sensor redundancy and of regular maintenance increases the costs. However, their designing is quite complex and needs a complete knowledge of the site dynamics and often a set of previously acquired monitoring data. In particular, the key-component of an EWS in the algorithm that governs the alarm activation, a complex and difficult task to address effectively because false negatives must be absolutely avoided and the number of false positives has to be as much little as possible. This is why very few examples of event EWS have been deployed so far (Badoux et al., 2008; Bossi et al., 2015; Gianora et al., 2013; Jacquemart et al., 2015).

In this work, we present a warning algorithm based on the real time processing of ground vibration data. We discuss the result of the application of the algorithm on data gathered in two years of monitoring in the Gadria basin, Northeastern Italian Alps. In 2014 this warning algorithm was implemented in the experimental debris flow EWS installed in that basin.

6.2 Methods

6.2.1 Advantages of ground vibration sensors

Most monitoring devices (force plates, stage sensors, video cameras, etc.) need to be placed very close or even in the channel bed where debris flows propagate, with the consequent danger of damage. GVDs can be installed along the torrent banks and this greatly diminishes the probability to being destroyed by an event. GVDs are also adaptable to the often extreme environmental conditions typical of mountain areas. Moreover, before the arrival of a debris flow at the cross section where a seismic sensor is installed, a gradual increase of the signal can usually be observed. This rise starts several tens of seconds before the passage of the debris flow front through the cross section where the sensor is installed. For geophones installed directly in the terrain, the signal may start rising up to one minute in advance (Figure 43).

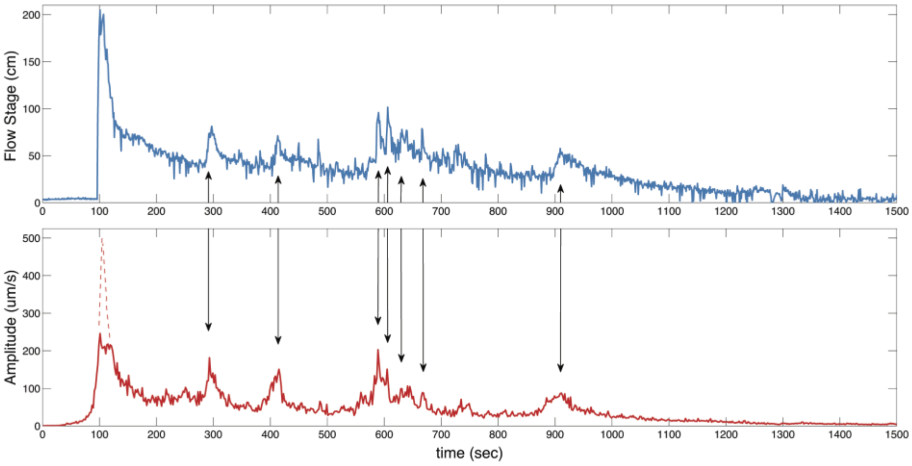

Figure 43 - Monitoring data of the debris flow that occurred on July 18, 2013 in the Gadria basin: hydrograph recorded by a stage sensor (above) and ground vibrations detected by a geophone installed at the same cross-section (station 3, see Figure 48). The Amplitude curve is partially saturated but the peaks produced by the main surges (black arrows) are clearly visible in both graphs. The main front waveform (dashed line) was reconstructed, thus this allows to appreciate how the Amplitude starts rising around 60 seconds before the hydrograph records the passage of the debris flow front.

Therefore, a further advantage of a GVD is its capability to detect the occurrence of a debris flow tens of seconds earlier than other types of devices. On the contrary, stage sensors start the detection only when the debris flow front has reached their position. This earlier detection can be precious if the sensors have to be placed very close to the infrastructure to protect, for instance a road where circulation have to be stopped with a traffic light (Arattano et al., 2014). Moreover, geomorphologic discontinuities located upstream from the monitored torrent reach, such a high check dam or a natural water fall, might even allow the detection of the arrival of the debris flows some hundreds of seconds in advance (Coviello et al., 2015a). GVDs can also detect the presence of subsequent surges behind the main front and, given the proportionality between the intensity of ground vibration and the flow height (Figure 43), they may also give information on the evolution of the flow height with time and even on the magnitude of the event, after calibration. All these features are particularly relevant when GVDs are used as warning sensors.

6.2.2 Synthetic protocol for using ground vibration sensors

An effective use the GVD output signal for both monitoring and warning purposes requires: (i) to make the correct choice of the seismic sensor to install, (ii) to establish the location, the number and the method of installation of the sensors, (iii) to define a proper sampling rate of the analogical signal, (iv) to set a suitable level of amplification of the digitalized signal, and (v) to choose the method of transformation of the ground vibration raw signal. In the following, these topics are addressed in detail.

Among the different GVDs employable to monitor debris flows, mono-axial geophones certainly are the most used device. Geophones are easy-to-install and low-cost sensors compared to classical seismometers and accelerometers. Their output is a voltage directly proportional to the ground vibration velocity in a specific working frequency band which depends from the natural frequency of the sensor. Consequently, this latter frequency has to be correctly chosen in order to have a flat response in an appropriate frequency range. According to Lahusen (1996), the typical peak frequencies of a debris flow range between 30 and 80 Hz, whereas debris floods produce ground vibrations with peak frequencies higher than 100. Huang et al (2007) observed in the Ai-Yu-Zi Creek (Nan-Tou, Taiwan) that at the surge front the peak frequencies range between 10–30 Hz while they range between 60–80 Hz at the flow tail. The spectral analysis of seismic monitoring data gathered in the Rebaixader catchment confirmed that the main frequency content of debris flows ranges between 10 and 60 Hz (Arattano et al., 2014).

Concerning the number of GVD to install, it must be noticed that at least two geophones are required, both for monitoring and warning purposes, (i) to estimate the velocities of main front and secondary surges (Arattano and Marchi, 2005) and (ii) to minimize false alarms due to simultaneous signals produced by earth surface processes occurring outside the monitored torrent reach (Coviello et al., 2015a).

The output voltage of a geophone is an analogical signal. This latter signal is subsequently digitalized and then recorded in a data-logger. Similarly to the choice of the geophone natural frequency, also the definition of the sampling rate has to be done considering the frequencies of the phenomenon under investigation. The choice of the sampling rate is often a compromise between the optimal theoretical needs and both environmental and instrumental limitations. This is a common problem the researchers have to deal with when they design a monitoring station. As an example, Navratil et al. (2013) were obliged to set a very low sampling rate value of 5 Hz.

In general, the mean background noise detected by a GVD is inversely correlated with the distance sensor-talweg. This latter distance may have a relevant impact on the early detection of the seismic waves generated by the debris flow front. The first arrival picking of the signal can be significantly anticipated installing the sensor at an appropriate distance from the channel (Coviello et al., 2015a). A the same time, the method of installation of the geophones strongly affects the amplification of the output signal (Abancó et al., 2012). Thus, different levels of electronic amplification should be provided in the monitoring equipment.

After the digitalization, the seismic signal is usually processed to reduce the amount of data that has to be stored (Arattano et al., 2014). There are two main methods that are employed for the processing of the raw signal: the transformation into Amplitude (Arattano, 1999) and the transformation into Impulses (Abancó et al., 2012). Especially if GVDs are employed for warning purposes, the method of Amplitude has a number of advantages: (i) the application of the method of Amplitude does not need any experimental threshold to transform the raw signal, like the method of Impulses does; (ii) the choice of this threshold value has an impact on the Impulses curve shape and on the possibility to detect the debris flow arrival in advance; (iii) the Amplitude waveforms are not affected by the choice of the sampling frequency, while the Impulses curves do (Arattano et al., 2015c).

6.2.3 Warning algorithms based on ground vibration

The transformation of the raw seismic data is only the first step needed to employ GVDs in debris flow EWSs. The information retrieved from the signal has then to be integrated in a set of rules that precisely defines a sequence of operations that govern the EWS, namely in a warning algorithm. To this aim, specific parameters driving the warning algorithm must be identified in the signal.

Most part of warning algorithms from debris flow proposed so far use static intensity threshold as main warning parameter (Abancó et al., 2012; Badoux et al., 2008; Gianora et al., 2013; Schimmel and Hübl, 2015). Then the algorithm activates the alarm only if the threshold is exceeded for a specific time interval (Badoux et al., 2008) or when another intensity threshold is reached by a different sensor (Schimmel and Hübl, 2015). Static intensity thresholds are intuitive and simple to adopt using a transformed Amplitude or Impulses signal but they has a number of limitations that mainly depend from the choice of the threshold values. In general, warning algorithms integrating static intensity thresholds are: (i) event-sensitive, because the magnitude and the dynamics (i.e. the velocity) of the debris flow event have a strong impact on the ground vibrations; (ii) network-sensitive, because the joint effect of the distance of the GVD from the channel and the geometry of the channel (e.g. presence of check dams or deposits) influences the signal intensity; (iii) prone to a high number of false alarms dues to impulsive signals produced by other ground vibration sources (e.g. earthquakes, seismic noise produced by vehicles, slope instabilities and torrential processes occurring in basins nearby).

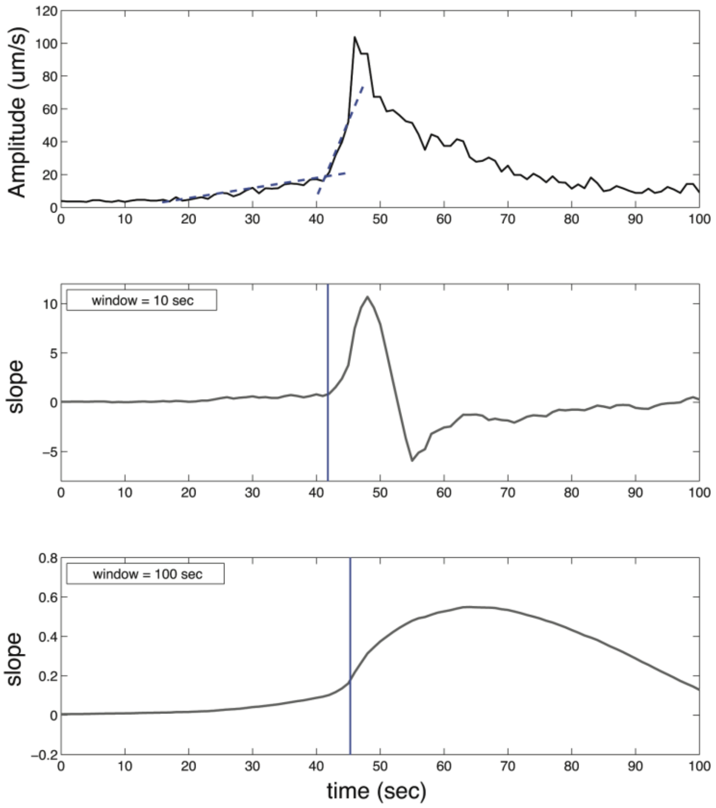

Figure 44 - The Amplitude curve and the inflection point that can be identified between the two lines that best fit the Amplitude curve before and after the change of slope (first panel); slope of the Amplitude curve calculated with a moving window of 10 seconds (second panel); slope of the Amplitude curve calculated with a moving window of 100 seconds (third panel).

In previous studies, another parameter was identified that can be used in warning algorithms, i.e. the slope of the Amplitude curve (Arattano, 2003). As mentioned before, the signal preceding the arrival of the debris flow wave at the cross section where the GVD is installed shows a gradual increase of its intensity. Some tens of seconds after, the signal presents a well defined change in slope, when a rapid increase of the signal takes place. An inflection point between the two lines that best fit the Amplitude curve before and after the change of slope can be identified, as well as a slope threshold that could be used as warning parameter Figure 44. The slope threshold could detect the arrival of the debris flow front some second before its passage at the cross section where the GVD is installed. However, the time window used to calculate the slope strongly affects the result. A short window (10 seconds) allows to detect the debris flow front with more advance then a long window (100 seconds) while this latter window is more effective if used to filter minor events or external seismic noise. Even if such an algorithm based on the slope of the Amplitude curve could be less case-sensitive and network-depended than one based on a static intensity threshold, the problem of the high number of false alarms would not be solved. A number of external disturbance and periodic fluctuations affect the seismic signal recorded along a torrent reach that can produce important changes of the Amplitude slope.

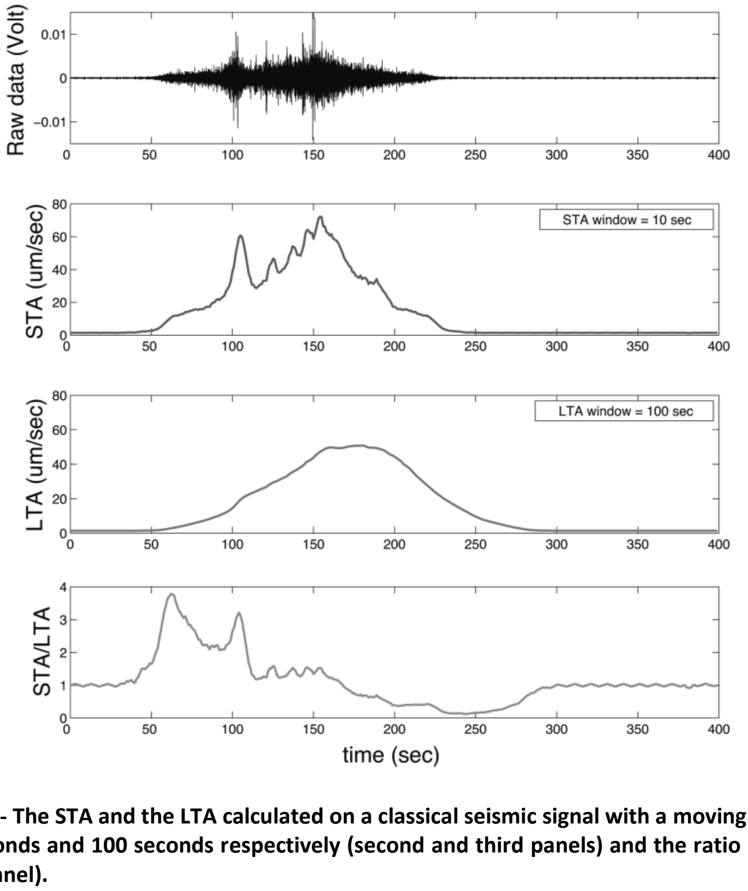

Figure 45 - The STA and the LTA calculated on a classical seismic signal with a moving window of 10 seconds and 100 seconds respectively (second and third panels) and the ratio STA/LTA (fourth panel).

Afterwards, a warning parameter that takes into account the velocity of variation of the seismic signal intensity and filters as much as possible any external impulsive noise source is needed. The Signal-to-Noise Ratio (SNR) is a measure widely used in geophysics that compares the level of a desired signal to the level of background noise. SNR generically is the dimensionless ratio of the signal power to the noise power contained in a recording. More in general, we would refer to SNR as the ratio of two averages of energy calculated on a short-term window (STA) and on a long-term window (LTA). STA/LTA plots are useful for finding glitches associated with seismic events (Figure 45). A pair of consecutive windows, one short window and a second longer window, are passed over the seismic data. For each window the average deviation from the signal mean is computed. The ratio of the short window's average deviation to the long window's average deviation (STA/LTA) tends to jump up when a glitch is encountered. For purely random white noise, the nominal ratio is one. Because seismic data is not white and because no filtering is applied to the data before calculating STA/LTA, the nominal ratio tends to be above unity.

A comparison among these three warning parameter is presented in Figure 46. The raw seismic signal produced by a debris flow that occurred in the Gadria basin has been transformed in an Amplitude curve, the slope of this latter curve has been obtained using a moving window of 100 seconds and the STA/LTA has been calculated with moving windows of 10 seconds and 100 seconds respectively. The three warning parameters are compared choosing thresholds equal to the midpoint of the distance between the first local maximum and minimum. Adopting a static intensity threshold, the choice of the threshold has a strong impact on the early detection of the debris flow arrival. A threshold slightly higher of lower would results in tens of seconds of advance or delay. Moreover, the Amplitude peaks produced by the different surges are highly variable and this suggests how this method can be case-sensitive. The issue of the threshold selection is also visible in the slope graph, that allows to detect earlier the debris flow arrival but at the same time presents higher peak values in correspondence of secondary waves. On the contrary, using the STA/LTA ratio the first onset arrival is clearly highlighted in significant advance and the peaks and the fluctuation of the signal that follow the debris flow front are then significantly damped. This allows to easily set a reliable threshold that would effectively detect the debris flow arrival after a proper calibration of the STA and LTA time windows lengths. Furthermore, the STA/LTA represents a measure of the SNR and this necessarily make it less event- and network-sensitive. In conclusion, the STA/LTA has been selected as the most effective warning parameter to integrate in a warning algorithm for debris flow EWSs. A systematic application of such an algorithm to a large Amplitude dataset will be presented in the following to investigate the potential of this method for filtering external seismic noise sources.

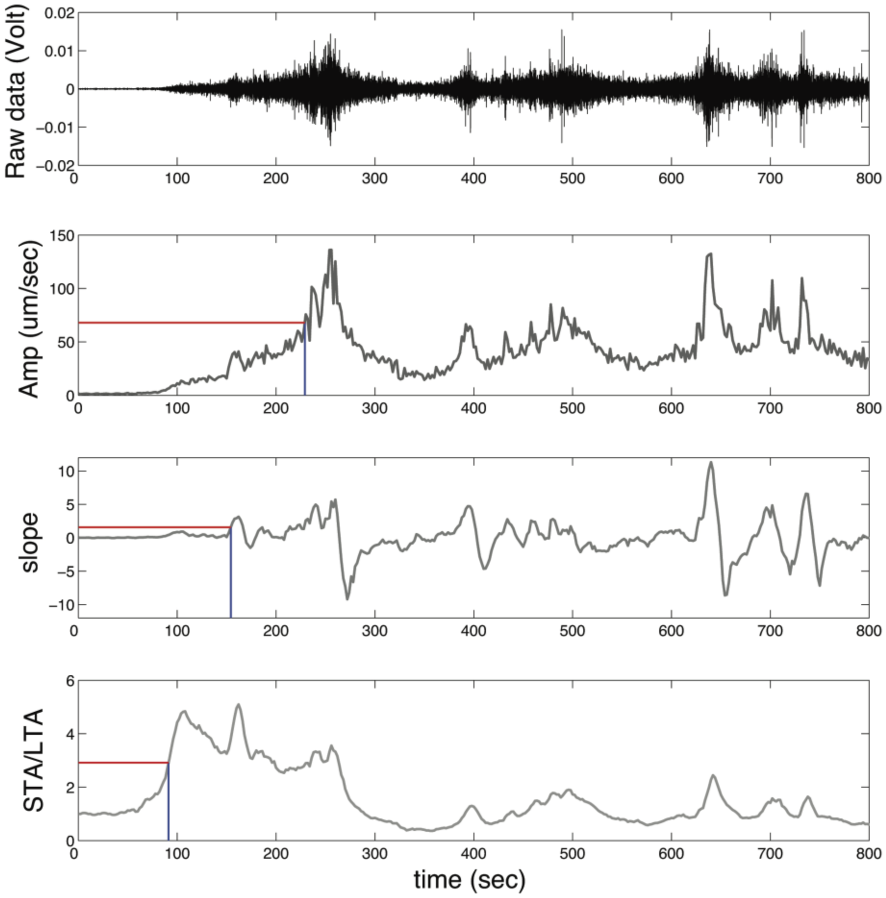

Figure 46 - The raw seismic signal produced by a debris flow that occurred in the Gadria basin, the Amplitude curve with a static intensity threshold equals to 68 um/sec, the slope of the Amplitude curve with a slope threshold equals to 1.57, the ratio STA/LTA with a threshold equals to 2.92.

6.2.4 ALMOND-F: an integrated debris flow monitoring and warning system

We designed an integrated monitoring and warning system mainly based on GVD data, capable of addressing the prescribed issues. Thanks to the collaboration with the company SIAP+MICROS, a prototype was developed, produced and then installed in 2013 in the pilot area of the Gadria basin, in the framework of the European Territorial Cooperation project named “Sediment management in Alpine basins: integrating sediment continuum, risk mitigation and hydropower” (SedAlp). After a first year of test, this prototype was improved and the new version, named ALMOND-F (Alarm and Monitoring System for Debris-Flow) was installed in 2014. This equipment is devoted to the multi-parametric monitoring of debris flows for documentation, research and warning purposes.

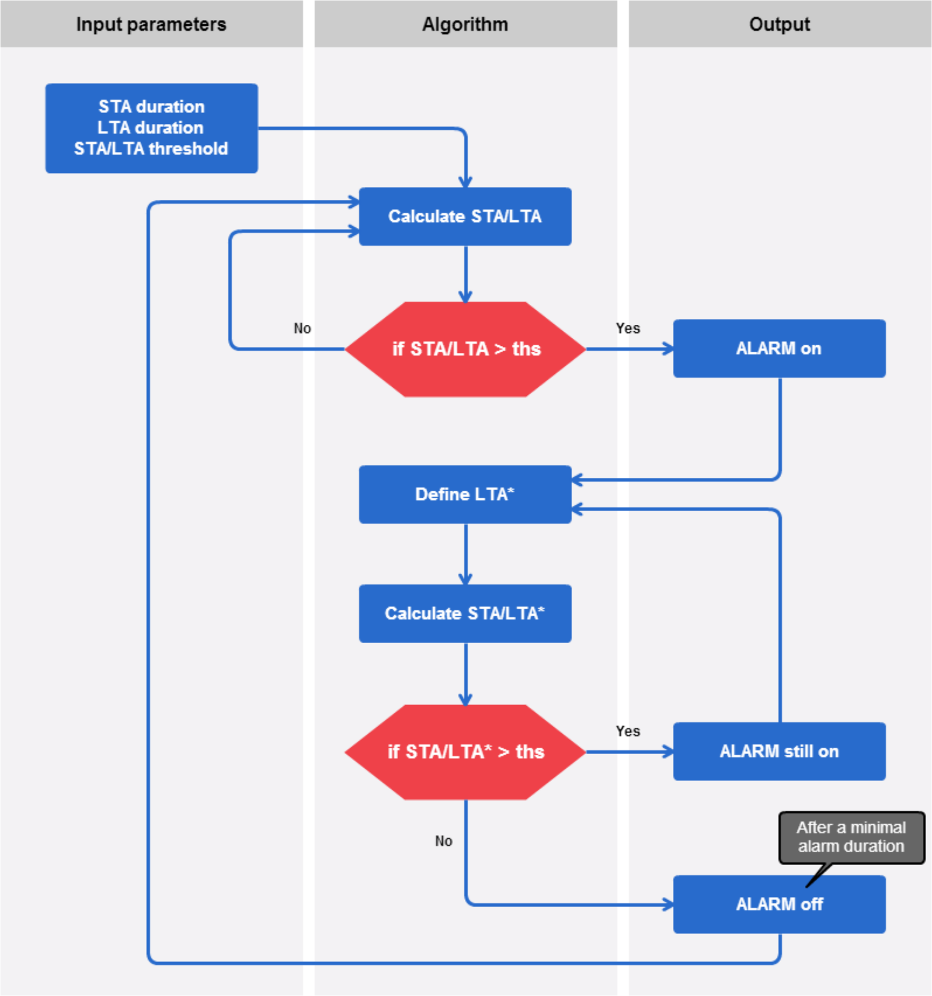

Figure 47 - Flow chart presenting the logic of the warning algorithm.

The standard version of ALMOND-F is composed by 3 geophones, 1 rain gauges and 1 stage sensor, placed along the torrent reach under investigation. The power supply is guaranteed by a 10 W solar panel. Considering the main frequency band needed to be investigated, 1-D vertical GVD with a natural frequency of 10 Hz have been adopted. The GVDs are wired to the recording unit, which is based on last version of SIAP+MICROS DA9000 data logger. In order to balance between the need of minimize the amount of data to store and the necessity to not lose information in the main frequency band, a sampling rate of 128 Hz has been adopted to convert to digital form the analogical signal. The geophone signal is acquired by a remote SIAP+MICROS analog-to-digital (AD) converter unit with eight programmable gains and a 24bit precision ranging from ±1V (gain = 1) to ±7mV (gain = 128). A spectral analysis of the raw signal is performed in real time and the AD converter interfaces to the DA9000 data logger via RS485 serial line in a proprietary master slave protocol. The recording unit allows to set different amplification values for each geophone, according to its distance from the torrent and its method of installation. In the following, the working principles of the monitoring system and the logic of the warning algorithm (Figure 47) are presented. In Figure 47 is represented the logical flow chart of the algorithm.

In normal flow conditions, the monitoring system works in “no-event mode”, recording a limited number of variables per second (Amplitude, maximum and minimum value of the raw signal, number of Impulses, main frequency and its band width, first four harmonics). Hereinafter, when we use the term Amplitude we refer to the output of the transformation of the analogical voltage signal with the method of Amplitude (Arattano et al., 2014). Second by second, for each Amplitude trace is computed the Short Term Averaging over Long Term Averaging (STA/LTA). The STA/LTA values represent the ratio between the average of the Amplitude values calculated on a short time window (STA) and on a long time window (LTA). The durations of these time windows have to be set as input parameters. Another input parameter is the STA/LTA threshold value that runs the “event-mode” recording. In case of activation of the event-mode, the system starts recording the raw signal.

The warning system works on the basis of the same parameters presented before, using the STA/LTA as warning parameter. When the STA/LTA threshold is exceeded, the alarm is activated and the last LTA value (LTA*) starts to be used to compute the ratio STA/LTA*. In geophysics literature, LTA* is usually named frozen or clamped LTA (e.g. Trnkoczy, 1998). Once the value goes back below the STA/LTA* threshold, the alarm is switched off and the system restarts to normally calculate STA/LTA. However, a minimal alarm duration can be set in order to take into account the time interval needed by the tail of the debris flow to travel from the cross-section where the warning system is installed to the area to warn, which is of course located downstream. The alarm is triggered only when the STA/LTA threshold is exceeded on at least two geophones. The non-simultaneousness of the threshold triggering on the two sensors is a further condition, more details on this latter point will be addressed discussed. To this aim, two geophones are enough but to have a minimal redundancy the installation of one more sensor is suggested. in addition to the parameters normally registered in “no-event mode”, during the “event-mode” recording the system also records a limited sample of raw data. A pre-trigger allows starting the raw data registration one minute before the triggering of the STA/LTA threshold.

6.3 Testing field for debris flow warning algorithms

The Gadria monitoring station is located at the confluence of the Gadria–Strimm channels, located in the Vinschgau-Venosta valley, Autonomous Province of Bozen-Bolzano, Italy (Figure 48). The general settings of the Gadria-Strimm basins and of the monitoring equipment are described in section 4.2.3 and 4.2.4. The seismic monitoring system used for this study is composed by three geophones installed along the left bank of the torrent (Figure 48 and Figure 49).

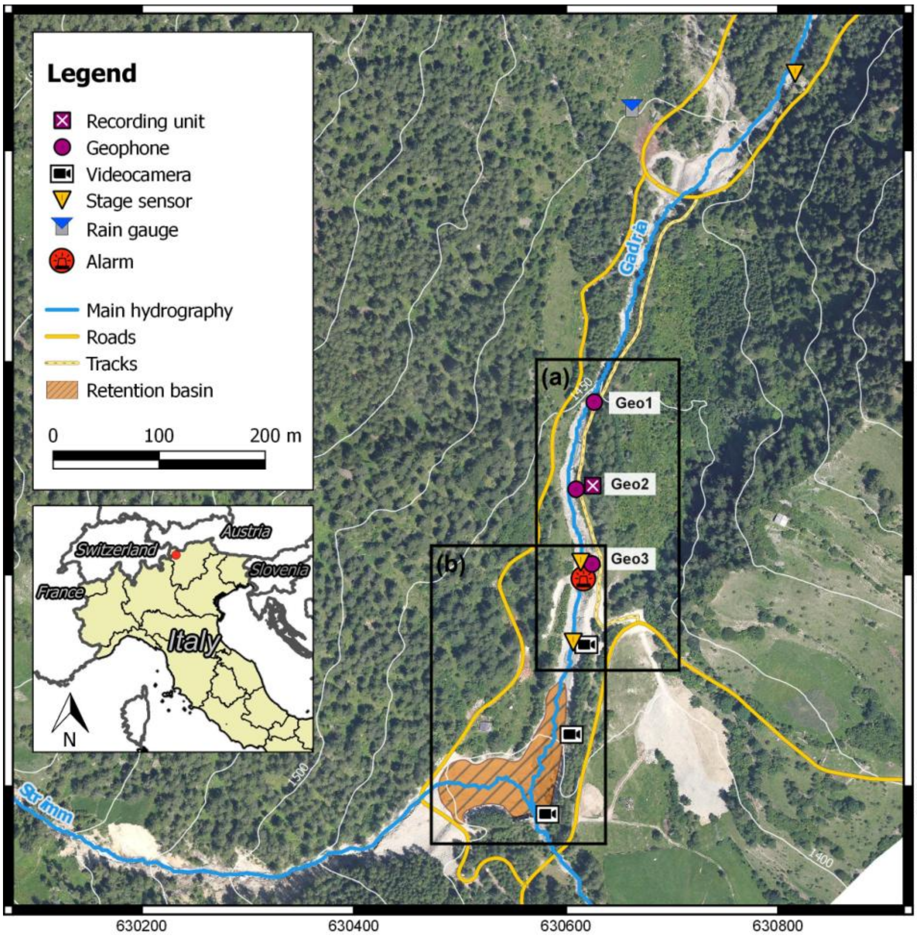

Figure 48 - Location of the experimental station ALMOND-F. The black frame (a) limits the Gadria testing field for debris-flow warning devices and algorithms, in (b) is emphasized the area and the sensors used for volume estimations. Background image courtesy of Bolzano Province, coordinate system: WGS 1984 UTM Zone 32NGadria–Strimm basins.

The first seismic monitoring data were collected in 2013 when the first stand-alone recording unit was set up in the thanks to the collaboration between CNR IRPI and the company SIAP+MICROS (Figure 49). This equipment was designed to contribute reaching the Sedalp project purposes, i.e. the standardization of the data collection methods and procedures in the field of sediment transport. The other aim of this instrumentation is to increase the public awareness on the functionality and the effective performances of a debris flow EWS.

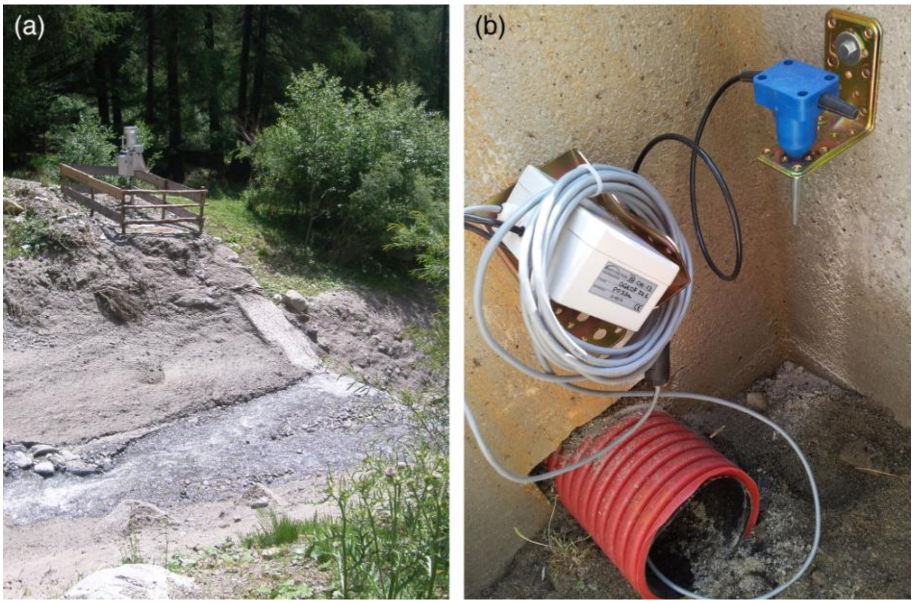

Figure 49 - (a) The recording unit installed on the left bank of the Gadria torrent, brushed by the debris flow event of July 18, 2013 (photo: L. Marchi); (b) the geophone 2 installed alongside the recording unit in the concrete manhole.

A typical question posed by geo-ethics specialists concerns the possible communication and educational strategies that should be adopted to transfer the value of the geosciences to society (Peppoloni and Di Capua, 2015). Which are the best methods to involve population, in this case about debris flow EWSs, to grant their proper workability? A first attempt could be providing the chance to easily and effectively divulge the results and make them easily perceivable and understandable by those people who are the actual, final end-users: administrators, decision makers and citizens. Devoting a specific reach of the Gadria torrent to the test of EWS and algorithms, and providing means to make visible the proper working of the system through the video camera recordings and a flashing light, represents an effort in the above mentioned direction (Arattano et al., 2015d). An EWS, in fact, cannot provide a complete safety for the people that it is devoted to protect, as a certain percentage of risk will always remain and false alarms will also possibly exist. The ideal location of such an installation is monitored basin where events occur with a high enough frequency to grant the possibility of a significant number of tests. The Gadria catchment provided such a valuable site.

In 2014, the warning algorithm described in the previous section was integrated in the recording unit and an experimental alarm system composed by a red flashing light was installed (Figure 48). The favorable characteristics of the Gadria basin, where one debris flow event per years on average occurs, no important roads or settlements need to be warned and several monitoring instrumentation is already installed (Comiti et al., 2014), allowed us to start using this catchment as warning algorithm test site. This semaphore has been installed in order to have a visual check of the warning system performances, but it is not a traffic light neither it has any real alert purpose. In fact, the red flashing light positioned in station 3 is visible in the upper right corner of the video recordings (Figure 50).

6.4 Results and discussion

The warning algorithm presented before was tested on the monitoring data gathered in 2013 and then integrated in the recording unit in 2014. Here following the results of the monitoring campaigns of 2013 (without alarm system) and 2014 (with alarm system) are presented, together with the analysis of the performance of the algorithm on the whole available seismic monitoring dataset gathered in the Gadria basin.

6.4.1 Debris flow event occurred on July 18, 2013

The debris flow recorded by the seismic monitoring system occurred on July 18, 2013. The volume of this event was estimated to be approximately equals to 10.000 cubic meters (Comiti et al., 2014). After the main front, six secondary surges flowed in the channel but the dynamics of the process was quite complex. These surges were composed by a succession of roll waves and clusters of blocks. The arrival of the main front was really spectacular, because of its height (more than 2 m at station 3, see Figure 50) and the contrast with the clear low flow forerunning the front. All these features are recognizable in the Amplitude graphs, in particular in the seismic trace recorded by the geophone 3 which is located in the cross section where a stage sensor is installed (Figure 43). The seismic waveform had the typical shape characterized by a sudden rise of the signal level corresponding to the passage of the main front. This ascending limb of the graph is followed by a more gradual decrease of the signal intensity, which rises again when the secondary surges propagate in the channel.

Figure 50 - Frames from the video camera recordings of July 18, 2013 at station 4. From above, from left to right: in (a) and (b), the main front arrival; in (c) and (d), two secondary surges; in (e) a late surge transporting a large boulder and in (f) the end of the flow process.

The flow was mainly erosive in the analyzed reach, with large entrainment along the channel. The transport of large boulders shows a “stop and go” pattern: during the flow (Figure 50e) large boulders stop approximately in the middle of the reach between two check dams, and are entrained when flow depth rises again. If the size of transported boulders is similar to (or greater than) flow depth, boulders protrude from the finer slurry and the recording of radar sensors depict the passage of such boulders, whose dynamics may differ from that of the slurry (Marchi, 2013). After the flow, the main deposits in the monitored reach were concentered along the right bank.

The warning algorithm was tested on GVD data recorded during this event and the results are presented in Figure 51. Although the raw seismic signal was saturated, especially on geophone 1 and 2, the performances of the algorithm are satisfying. The algorithm was applied to the Amplitude curves (Figure 51a) firstly using tentative values of STA and LTA durations (Figure 51b). The debris flow front is quite well identified but also two false alarms are visible, few minutes before the arrival of the main front. These latter false alarms are produced by little and short rises of the Amplitude. Furthermore, the first false alarm occurring around t = 100 sec reaches STA/LTA values higher than those produced by the debris flow front. Consequently, a calibration of both STA and LTA time windows duration was performed and the results presented in Figure 51c. Adopting a STA/LTA threshold higher than 3 is possible to avoid both false alarms and to correctly detect the passage of the debris flow main front.

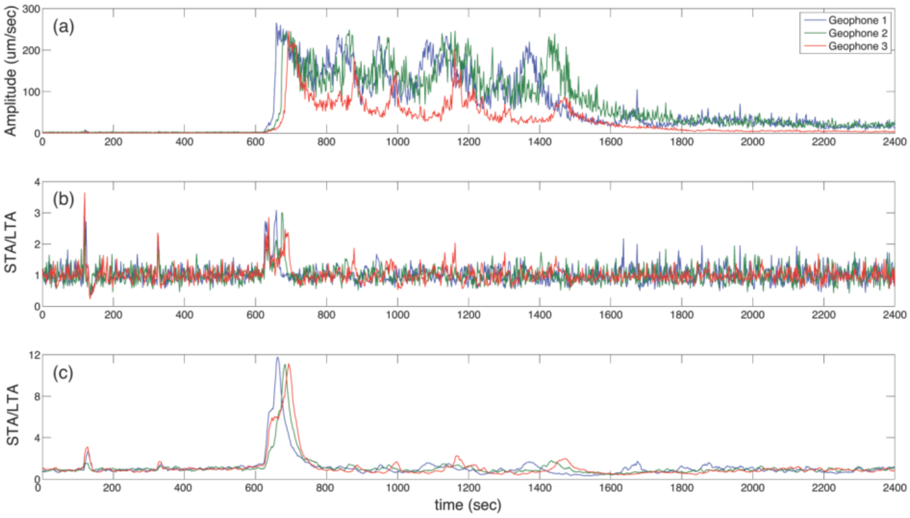

Figure 51 - First row: Amplitude curves of the debris flow occurred on July 18, 2013 recorded by the three geophones installed at Gadria; second raw: tentative STA/LTA; calibrated STA/LTA.

6.4.2 Debris flow event occurred on July 15, 2014

On July 15, 2014 another remarkable debris flow event occurred in the Gadria basin. This time, the main front was preceded by a precursory liquid surge. It was possible to count five main secondary waves with, again, succession of roll waves and clusters of blocks (Figure 52). In the Amplitude recordings it is possible to recognize the passage of the precursory liquid wave, of the main front and of the secondary surges (Figure 53 and second row of Figure 54). The duration of the whole debris flow phenomenon (around 30 minutes) was slightly larger than the one of the 2013 event (20 minutes), while the order of magnitude of the volumes was similar. In 2013, the maximum Amplitude values were recorded in correspondence of the main front arrival while in 2014 the highest ground vibrations were produced by a secondary surge. In fact, in 2014 the velocity of the front was considerably slower than in 2013, as a consequence the Amplitude graphs raise more gradually reaching slowly the first relative maximum.

As already stated before, the warning algorithm integrated in the recording unit during the spring of 2014 activates a red light visible in the upper right corner of the video recordings (Figure 52). During the 2014 debris flow event, the alarm was triggered by the ground vibrations produced by the passage of the precursory surge. In correspondence of section 3, the one focused in the video recordings, this advance results even larger. In fact, the algorithm activates the alarm when the STA/LTA threshold is exceeded on at least two geophones and this condition was fulfilled by all sensors pair-wise but firstly by geophone 1 and 2. As a consequence, the red flash light installed in station 3 was activated 3 minutes before the passage of the main front through this cross-section (Figure 52b). It would be always recommended to install the GVDs far enough upstream from the area to warn, in order to grant a more effective warning saving some precious tens of seconds.

In Figure 54 the comparison among the raw data, the Amplitude graphs and the spectrograms of the precursory surge and of the main front of the debris flow event occurred in 2014 in the Gadria basin are presented. As already stated before, ALMOND-F allows the recording of a limited set of raw data (with a sampling rate equals to 128 Hz) when the STA/LTA threshold is exceeded. Data from geophone 1 were partially saturated during the passage of the main front but this did not invalidate the output of the warning algorithm. The saturation of the signal (Table 6) certainly is a limitation for performing a reliable spectral analysis, as well as the limited working frequency range of the deployed sensors. The mono-dimensional geophones installed at Gadria (Geospace 20DX) have a natural frequency of 10 Hz, as a consequence their flat response in V/um/sec starts approximately from this latter value of frequency.

Table 6 - Distances sensor-talweg at Gadria, amplification values set at each station and relative full scale.

	Detection distance (m)	Amplification	Full scale (Volt)
Geophone 1	8.3	32	0.0315
Geophone 2	5.8	32	0.0315
Geophone 3	10.9	64	0.0156

Figure 52 - Frames from the video camera of the debris flow event that occurred on July 15, 2014 in the Gadria basin. In the upper right corner of each frame is visible the flashing light. From above, from left to right: (a) the torrent before the process (light off); (b) the precursory surge arrival (light on); (c) the main front (light on); (d) and (e), two secondary surges (light on); (f) the end of the flow process (light off).

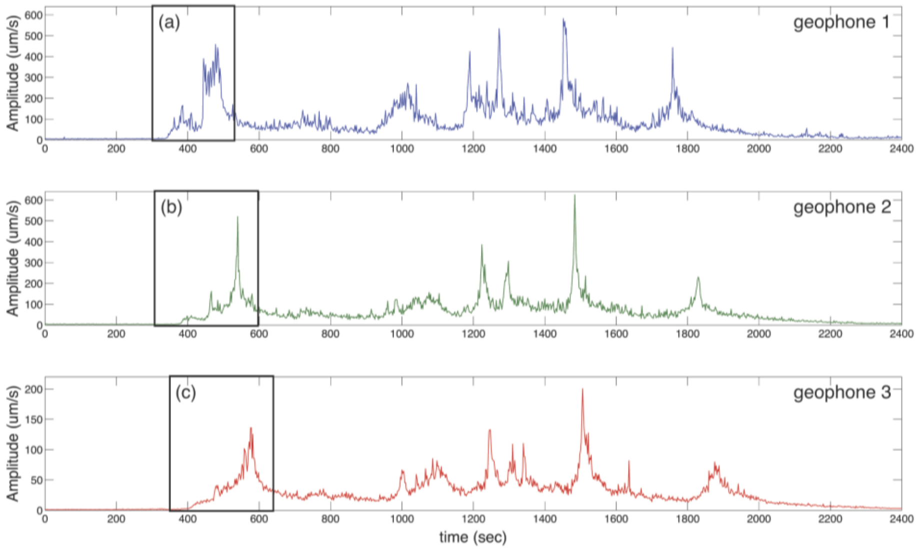

Figure 53 - Amplitude curves of the debris flow occurred on July 15, 2014 in the Gadria basin. The black frames contain the portions of the signals corresponding to the precursory surge and the main front, enlarged in Figure 54.

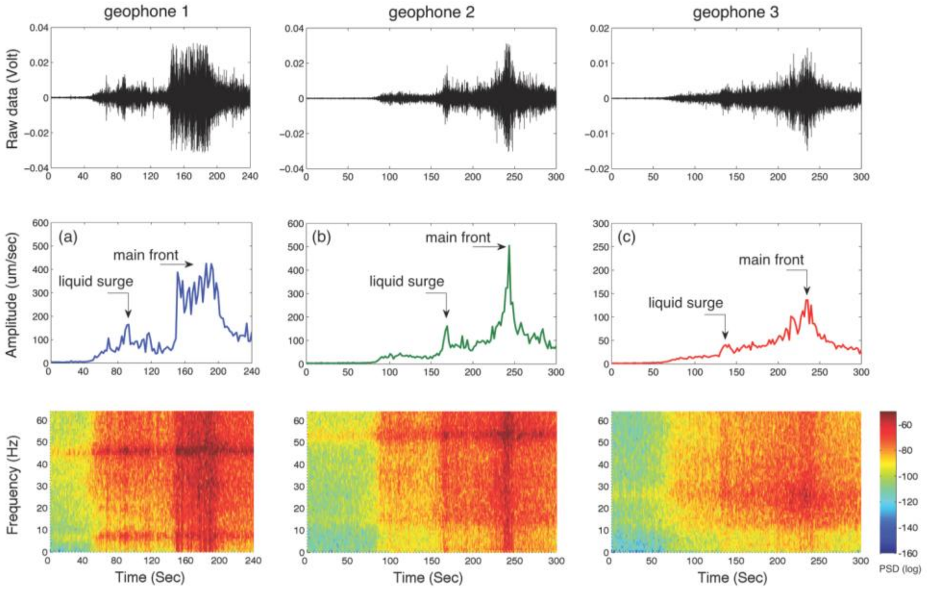

Figure 54 - The raw signals (first row), the Amplitude graphs (second row) and the spectrogram (third row) of the seismic recordings of the 2014 debris flow main front. Note differences in vertical scales.

However, the spectral analysis gives some preliminary, interesting information that deserves to be discussed. In particular, in the spectrogram related to the signal recorded by geophone 3, during the passage of the first liquid surge and of the main front (Figure 54c) it is possible to observe an emergent onset of the main frequencies included in the range 10-30 Hz that precedes the rise of the Amplitude curve. Furthermore, at geophone 2 the main frequencies appear to be significantly higher, above 50 Hz. Can these differences in the spectrogram shapes be due to the different detections distances of geophone 2 and 3 (Table 6), thus to the attenuation of high frequencies, or we are in presence of some external disturbance or even aliasing? This point will be further investigated in future.

6.4.3 Analysis of the performances of the algorithm

The warning algorithm was tested on the whole available dataset gathered in the Gadria basin during both 2013 and 2014 monitoring seasons. Data from 54 days of complete and continuous monitoring carried out in 2013 (from July 13 to September 5) are analyzed. In 2014, 51 days of recordings performed in from June 27 to August 20. In Table 7 the results of the simulation are presented. As already stated before, the two debris flows event occurred in this time period were correctly detected by the algorithm (True Positives = 2, no False Negative). In the first sub-set of data only 1 false positive was recorded while in the 2014 sub-set 2 false alarms were produced (total number of False Positives = 3). These results are of particularly significance because, thanks to the continuous monitoring performed in the Gadria basin during the last two years, we do not have any lack of information about debris flows occurrence. As a consequence, we are certain that the false negative (FN) are really equal to zero.

Table 7 - Application of the warning algorithm to the whole available monitoring dataset gathered in the Gadria basin during 105 days of recordings. To quantify the True Negatives (TN) is possible to assign to the variable n the number of hours of monitoring (1 hour is the order of size of the duration in time of a typical debris flow event at Gadria). As a result, the number of TN would be equal to 2516.

	Debris flow	**No debris flow**
Test positive	True Positive TP = 2	False Positive TP = 3
Test negative	False Negative FN = 0	True Negative TN = n-3

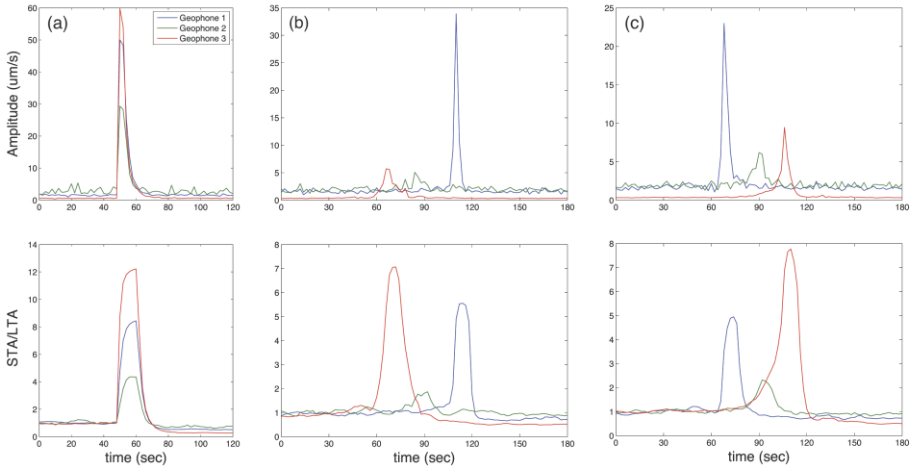

Figure 55 - Amplitude (first row) and STA/LTA values (second row) of: (a) the false alarm recorded on July 31, 2014; a punctual source of noise recorded on June 28, 2014 moving along the torrent firstly in upstream (b) and therefore in downstream (c) direction.

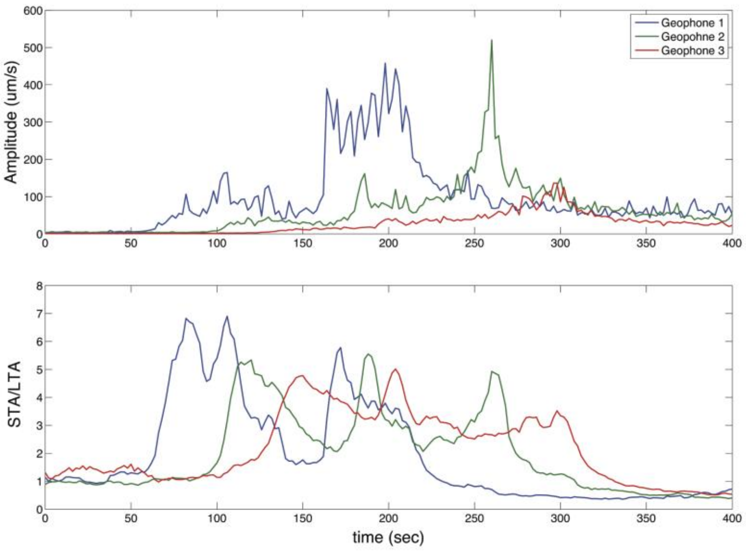

Figure 56 - Amplitude (first row) and STA/LTA values (second row) of the signals produced by the debris flow event occurred on July 31, 2014 in the Gadria basin.

However, these results can be even improved. Analyzing in deep the false positives, it comes to light that they are generated by simultaneous signals, characterized by short durations of few seconds, recorded by all the three geophones (Figure 55a).

This kind of signals can be produced by regional earthquakes or, given their relative low amplitudes, the occurrence of slope or torrential processes outside the monitored torrent reach (Coviello et al., 2015a). To minimize false alarms due to these external sources, a non-simultaneousness criterion in the threshold triggering can be adopted. If the alarm is activated when the STA/LTA ratio exceeds the threshold on at least two geophones but only if progressively from upstream to downstream, the number of false alarms would be reduced to 0.

We also want to stress the importance of setting a minimum time over threshold of the STA/LTA ratio on at least two sensors to activate the alarm. Without considering this latter point, another class of false alarms would appear, produced when the threshold is exceeded progressively sensor-by-sensor. The signals producing these false alarms are likely due to a moving, punctual source of noise like a motorcycle or a small vehicle passing along the torrent and going upstream (Figure 55b) or downstream (Figure 55c). Indeed, along the left bank of the Gadria stream there is a narrow track occasionally used by rangers. On the contrary, a debris low can be sketched like a linear source of ground vibration moving downstream in the channel, producing longer signals and STA/LTA curves (Figure 56).

6.4.4 Validation of the warning algorithm

The algorithm was then tested on the whole seismic dataset collected in the Marderello basin in 2013. The Marderello is a well-known mountain basin located in Western Italian Alps prone to produce mud flow events (Turconi et al., 2015). The sketch of the Marderello monitoring network and the general description of the basin, together with a number of torrential processes occurred in that period, are presented in Chapter 4. Data from 102 days of continuous monitoring carried out during the 2013 monitoring season (from June 26 to November 12) are analyzed. The same time windows length used to calculate STA and LTA and the same STA/LTA threshold calibrated at Gadria were used. In Table 8 the results of the simulation are presented.

The small mud flow that occurred on July 17, 2013 (Figure 57b) was correctly detected by the warning algorithm (Figure 57d). Analyzing in detail the data from this event, it also comes to light that the precursory surge (Figure 57a) could have been activate an alarm (Figure 57c) significantly before the arrival of the main front. However, the presence of the simultaneous peak due to the water fall located upstream the monitoring network makes things more complicated. A STA/LTA threshold equals to 4 would be exceeded progressively from by geophone 1, 2 and 3 thanks to the signal rising preceding the simultaneous peak (Figure 57c). Data from further, future mud flow events will be very precious to effectively integrate the water-fall derived information in the warning algorithm.

Table 8 - Application of the warning algorithm to the whole available monitoring dataset gathered in the Marderello basin in the 2013 summer season (101 days of recordings).

	Mud flow	**No mud flow**
Test positive	True Positive TP = 1	False Positive TP = 11
Test negative	False Negative FN = 0	True Negative TN = n-11

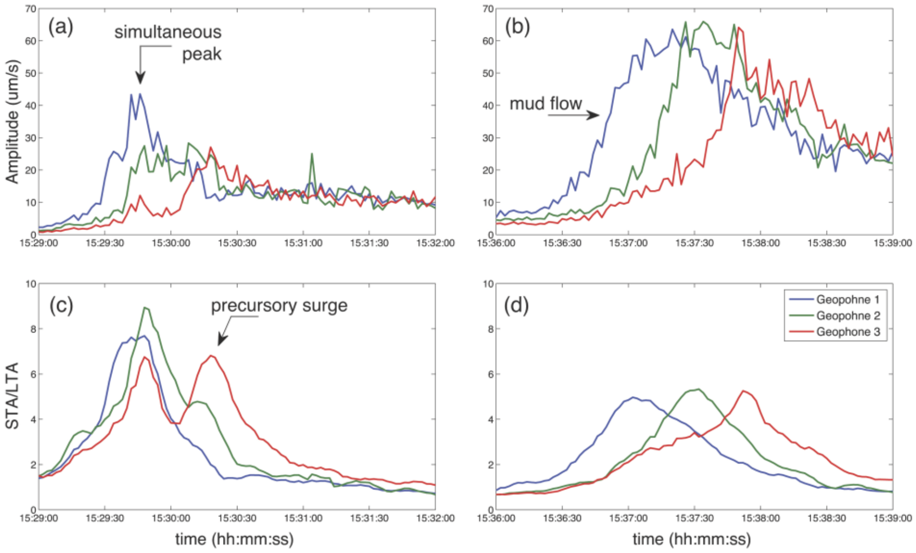

Figure 57 – Amplitude values (first line) and STA/LTA values (second line) of the mud flow event that occurred in the Marderello basin on July 17, 2013.

The small mud flow event occurred on August 8, 2013 did not exceeded the STA/LTA threshold. In fact, the magnitude of this event was so small that the stage sensor did not record the flow. As a consequence, it can be considered a torrential process not representing a hazards thus it was not classified as a false negative.

Concerning the false positives, the results can be again improved filtering the simultaneous signals recorded by the whole network. In that way, 3 false positives would be avoided. Furthermore, the application of the non-simultaneousness criterion in the threshold triggering would contribute to minimize the number of false alarms. In fact, 4 false positives were produced because the STA/LTA threshold was exceeded on at least two geophones progressively from downstream to upstream. All things considerate, a final number of 4 false positives was produced in the Marderello basin during the 2013 monitoring campaign.

In conclusion, the warning algorithm can be effectively applied to other basins where different typologies of events occur, i.e. mud flow. In particular, the employment of STA and LTA time windows and STA/LTA threshold values previously calibrated is successful, making the STA/LTA a non site-specific warning parameter. Furthermore, the algorithm is not sensitive to the event magnitude, this corroborate the choice of STA/LTA as warning parameter.

6.5 Future developments of the algorithm

Real time processing of high frequency seismic data would give significant information useful for early warning purposes. Signals related to mass movements have been identified by using broadband seismic networks around the world (Allstadt, 2013; Deparis et al., 2008; Hibert et al., 2011; Moretti et al., 2012). Common spectral characteristics including emergent onsets, slowly decaying tails and spectrograms with triangular shapes have been documented by several authors (Dammeier et al., 2011; Suriñach et al., 2005). Yamada et al. (2012) determinate locations and volumes of a swarm of landslides caused by a typhoon using seismological back-projection technique. The spectral analysis of high-frequency noise recorded by an array of seismic stations in the Himalayan region showed the occurrences of transient events during a monsoon season associable with debris flows events and intense bed load transport (Burtin et al., 2009). As the unpredictability and frequent location in remote areas of catastrophic landslides make observations of their dynamics rare, the use of real-time detection and inverse modeling of teleseismic data to characterize the dynamic of process would be of great potential (Ekström and Stark, 2013).

But concerning debris flow monitoring at catchment scale, high frequency monitoring data gathered with broadband seismometers are still scarce. Recently, in the Illgraben basin it was observed that a seismic sensor can detect a approaching flows before they reach the in-channel location nearest the station, giving rise to a progressive increase of registered seismic energy (Burtin et al., 2014). In the same work, a systematic energy increase along the channel was noticed, presumably in response to the entrainment of channel bed material and/or hillslope inputs. On the contrary, on the fan a decrease of seismic energy was observed. The authors stated that these trends may reflect changes in the sediment load of the propagating flows.

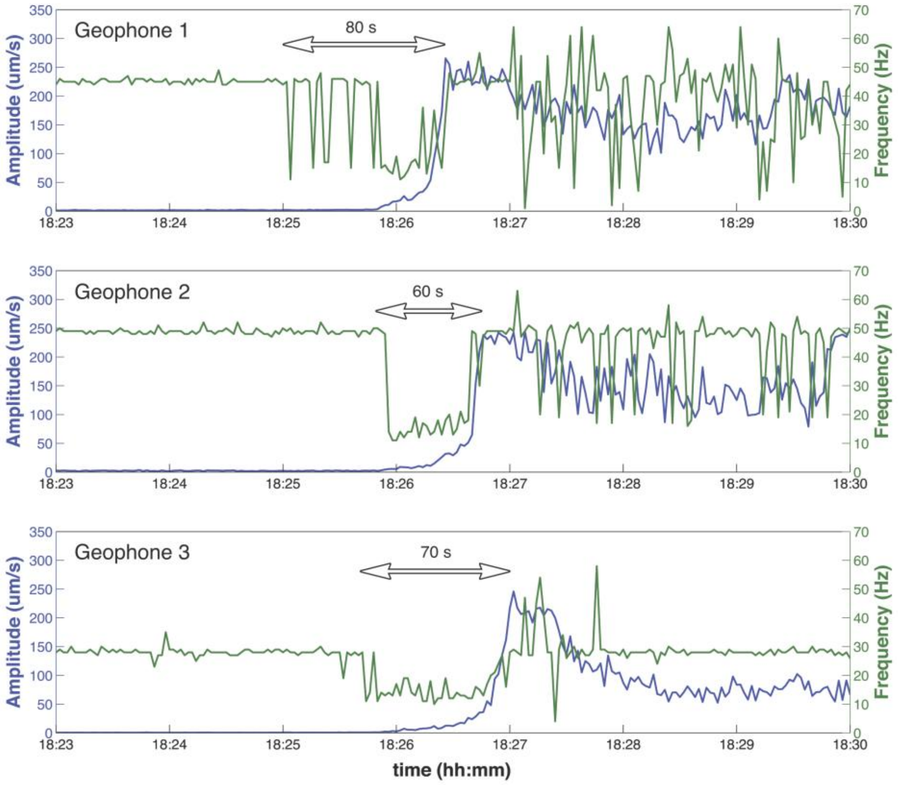

Figure 58 - Trend of the fundamental frequency (green line) and of the amplitude (blue line) of the debris flow occurred in the Gadria basin on July 18, 2013 before and during the arrival of the main front at each geophone. At the beginning of the rise of each amplitude graphs the main frequency suddenly drops to about 10 Hz and remains at that value until the arrival of the front.

The data gathered in the Gadria basin during the debris flow event that occurred on July 18, 2013 show how the main frequency computed in real time and recorded by ALMOND-F displays a rapid decrease some tens of seconds before the rising or the amplitude curves (Figure 58). Thus the spectral analysis seems to anticipate the information about the debris flow front arrival achievable from the amplitude curves. The main frequency recorded by the three GVDs reach values close 10 Hz, which are in agreement with the observations made by several authors on the main frequency content of debris flow fronts (Arattano et al., 2014; Burtin et al., 2014; Huang et al., 2007; Lahusen, 1998). The stable frequency values recorded before this drops to 10 Hz are likely related to electrical interferences. On the other hand, it has to be noticed that the spectral analysis of the portion of the signals recorded after the amplitude peaks is not reliable because of the signal saturation showed in Table 6.

As already mentioned before, a reliable spectral analysis would be of particular interest to further develop the warning system. The waveform recorded by geophone 3 during the debris flow that occurred in the Gadria basin on July 18, 2014 was surely not affected by saturation and was thus investigated in deep. Flow stage data are also monitored at the same station where this latter geophone is installed. Moreover, that cross-section is visible in the video recordings and (Figure 59). In the spectrogram produced using raw data recorded at station 3 (Figure 60), it is possible to observe an emergent onset of the main frequencies included in the range 10-30 Hz that significantly precedes the rise of the Amplitude curve. Moreover, in correspondence of the passage of the secondary surges, narrow signals covering the whole spectra are produced (Figure 60b and c).

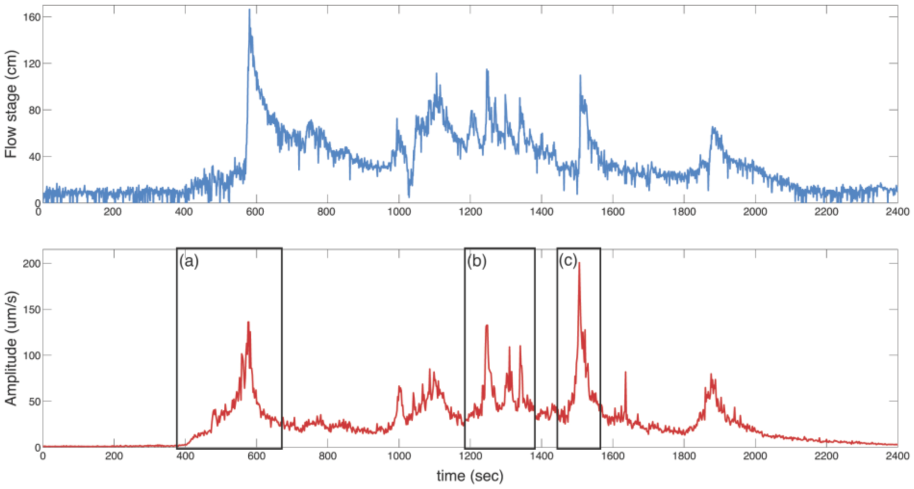

Figure 59 - Hydrograph recorded by a stage sensor (above) and ground vibrations detected by a geophone installed at the same cross-section (station 3, see Figure 48) of the debris flow occurred on July 15, 2014 in the Gadria basin. The black frames contain the portion of the signal analyzed in frequency domain in Figure 60.

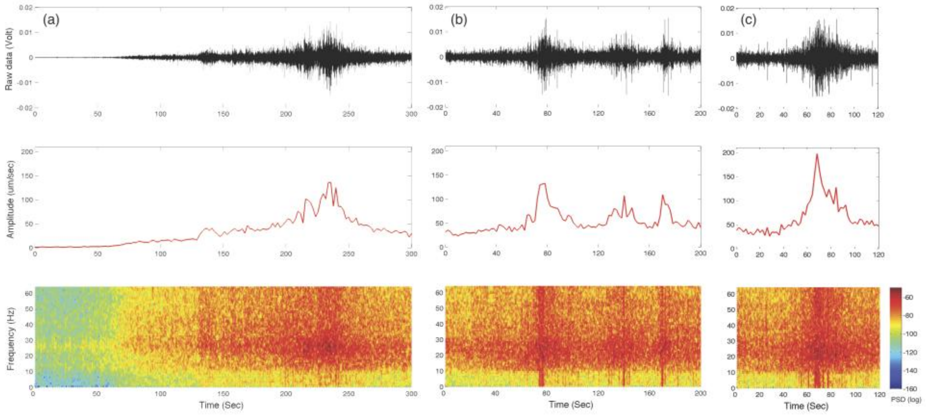

Figure 60 - Raw signal (first row), Amplitude curves (second row) and spectrograms (third row) of the main front and of some subsequent surges of the recordings of geophone 3.

This particular feature could be very useful for warning purposes, (i) offering a mean to better recognize the occurrence of a debris flow and distinguishing it from other type of phenomena, thus preventing the issue of false alarms, and (ii) allowing a further instrument of early detection of the phenomenon. If confirmed and validated by using broadband seismic sensors, this information could be used to further enhance the performances of the warning algorithm. However, it should be noticed that to this aim a real time processing of the seismic signal in frequency domain would be needed. A simplified spectral information such as the main frequency can be easily integrated in a warning algorithm while the interpretation of a complete frequency analysis (i.e. the spectrogram) certainly is difficult to perform in real time. Moreover, some work still remains to be done in order to infer reliable information about what kind of processes is occurring in the catchment and where.

7 Conclusions and future developments

A growing number of studies adopt passive seismic monitoring techniques to investigate slope instabilities and landslide processes. These techniques are attractive and convenient because large areas can be monitored from a safe distance. This is particularly true when the phenomena under investigation are rapid and infrequent mass movements like debris flows. Different types of devices are used to monitor debris flow processes, but among them ground vibration detectors (GVDs) present several, specific advantages that encourage their use. These advantages include: (i) the possibility to be installed outside the channel bed, (ii) the high adaptability to different and harsh field conditions, and (iii) the capability to detect the debris flow front arrival tens of seconds earlier than contact and stage sensors.

GVDs can provide relevant information on the dynamics of debris flows such as timing and velocity of the main surges. However, the processing of the raw seismic signal is usually needed, both to decrease the amount of data that need to be recorded and for power supply limitations. With this objective, the methods of Amplitude and Impulses are commonly adopted to transform the raw signal to a 1-Hz signal that allows for a more useful representation of the phenomenon. In that way, peaks and other features become more visible and comparable with data obtained from other monitoring devices.

The processing of the signal also allows to obtain a more effective representation of waveforms, useful to distinguish between debris flows and other types of field and torrent processes (i.e. debris floods, rockfalls, slope failures, etc.). As far as these two purposes are concerned, the results presented in this thesis reveals that the method of impulses requires particular attention in the choice of the threshold for the counting of impulses. The choice of a too low threshold might in fact impede a correct differentiation between the different surges of the flow and their relative dimensions. On the contrary, the choice of a too high threshold allows the identification of the correct proportions between the different surges and secondary waves, but might lose the smaller of them.

The recordings of Marderello monitoring network have also showed that a GVDs network might even detect debris flows or mud flows that occur in torrents nearby. The presence of geomorphologic discontinuities like high waterfalls or check dams in the monitored basin can also produce seismic recordings that need to be distinguished from the passage of a debris flow. The fall of the main front of a debris flow event might in fact be detected by the seismic sensors from a great distance, producing simultaneous signal peaks that can be easily recognized in the recordings of different geophones placed along the torrent. This information can be particularly useful for the development of warning algorithms, which should take them into account to avoid or at least reduce the possibility of false alarms.

One of the expected outputs of the European project named SedAlp was the draft of a protocol to standardize the data collection methods for debris flow monitoring. In the framework of this project, an integrated recording unit capable of providing different types of standardized performances for debris flow monitoring has been designed in collaboration with the company SIAP+MICROS and then installed in the pilot area of the Gadria basin. A warning algorithm that computes in real time the GVDs data recorded by this stand-alone monitoring system has been developed and presented. In particular, we focused on a debris flow event that occurred in 2014 and was properly detected by the algorithm. The alarm was triggered by the ground vibrations produced by the passage of the precursory surge at the first two sections, more than one minute before the arrival of the main front. The red flashing light installed at section 3 to provide a warning visual test was activated three minutes before the passage of the main front through this cross-section. The alarm lasted for the whole duration of the flow, correctly switching off after 20 minutes.

Testing the algorithm on the whole Amplitude dataset recorded during both summers 2013 and 2014 in the Gadria basin, only 3 false alarm where produced after calibration of the algorithm input parameters (STA and LTA time windows, STA/LTA threshold). The two debris flows event that occurred in this time period were correctly detected by the algorithm (True Positives = 2, no False Negative). The false positives were generated by simultaneous signals, characterized by short durations of few seconds, recorded by all the three geophones. Thus to eliminate these false alarms is possible using a non-simultaneousness criterion for the threshold triggering. If the alarm was activated when the STA/LTA ratio exceeds the threshold on at least two geophones but only if progressively from downstream to upstream, the number of false alarms would reduce to 0. These results are of particularly significance because, thanks to the continuous monitoring performed in the Gadria basin during the last two years, we do not have any lack of information about debris flows occurrence.

The warning algorithm was then validated using the seismic dataset collected in the Marderello basin during the 2013 monitoring campaign. The same STA and LTA duration and the same STA/LTA threshold calibrated at Gadria were used to perform the simulation. The small mud flow that occurred on July 17, 2013 was correctly detected by the algorithm and a number of 4 false alarms was produced.

The next step of this research activity would be the application to a real site to warn, where the algorithm would be integrated in a complete EWS mainly based on GVDs. This EWS would trigger alarms in the form of flashing lights and audible signals at channel crossings downstream and disseminate in real time the information to local authorities. However, we have to say that debris flow warning may not be only based on geophone data alone. In case of application to a real EWS, sensor diversification and redundancy would be of paramount importance. Furthermore, the presence of a debris flow EWS could induce a false feeling of safety, as a consequence the importance of a proper management and maintenance of the systems has to be stressed. It is worth remembering that the risk never overthrows to zero, even in presence of the best EWS. The residual risk may be reduced if a long-term monitoring is ensured, together with a complete and continuous efficiency of the system. In this context, in order to develop and optimize warning algorithms and procedures, the possibility to have a long-term dataset of monitoring data is essential.

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