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DEBRIS-FLOW MONITORING STATIONS IN THE EASTERN PYRENEES. DESCRIPTION OF INSTRUMENTATION, FIRST EXPERIENCES AND PRELIMINARY RESULTS

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ABSTRACT

Monitored observation stations represent a fundamental tool to properly investigate the initiation, flow behaviour and accumulation of debris flows. In the recent years, tree different monitoring stations have been built up in the Eastern Pyrenees. The instrumentation of all of them consists of four geophones and a rain gauge, while two of them also have an ultrasonic device and one site a video camera. First experiences regarding the set-up and calibration of the different devices indicate that debris-flow monitoring is a complex task and requires knowledge of different research areas. In particular, qualified electronic skills are essential. The preliminary results show that especially the Senet test site, with its initiation area in a steep and voluminous glacial deposit, presents a high debris-flow activity. Several events were recorded during the first year test phase and the analysis of precipitation data showed that most of the debris flows were triggered by short duration-high intensity rainfalls. The interpretation of the monitoring data related to the flow behaviour was not easy, because only geophone measurements, rainfall data and post-event field observations were available for the process analysis in most of the events. Thus, the visual information of a video camera is very helpful to carry out the calibration of monitoring data and to clarify doubts of interpretation.

Key words: *monitoring, ground vibration, rainfall threshold, Pyrenees*

INTRODUCTION

Field observations of moving debris flows by means of monitoring stations are of great importance to improve understandings of triggering, flow behaviour and accumulation mechanisms. Upon the knowledge of the authors, in Europe debrisflow monitoring stations are only situated in the Alps: Italy (Berti *et alii*. 2000; Marchi *et alii*. 2002), Austria (Huebl & Kaitna 2010) and Switzerland (Hürlimann *et alii*. 2003a; Badoux *et alii*. 2009), while other stations are located in China (Zhang 1993), Japan (Suwa *et alii*. 2009), Taiwan (Yin *et alii*. 2007) and USA (La Husen 2005) among others. However, no test site is located in a catchment affected by Mediterranean climate.

In the Eastern Pyrenees, debris flows are no as reported as in other mountain ranges, but can cause important damages as shown for example by the events occurred in 2008 (Portilla *et alii*. 2010). In order to improve the knowledge on the triggering conditions and the dynamic behaviour, three monitoring systems in the Eastern Pyrenees have been set up.

In the following, the monitoring systems installed in the test sites will be described and the first results and experiences will be discussed. The results presented here come from one of the sites, the Senet catchment, which revealed a high activity during the first year test phase.

GENERAL SETTING

The Eastern Pyrenees limit the Spanish region of Catalonia from France and include the Principality of Andorra (Fig. 1). The highest peaks are located at the axis range and reach almost 3000 m a.s.l.

From a geological point of view, two zones are clearly distinguishable (e.g. Muñoz, 1992): i) the Axial Zone that corresponds to the paleozoic basement, and ii) the covering layers that form the outer zones at both, northern and southern sides of the range. Our study concerns the Axial Zone and southern outer zone (here called Pre-Pyrenees). The basement consists almost entirely of igneous and metamorphic Paleozoic rocks formed and tectonised during the Hercinian orogeny and deformed again during the Alpine orogeny. The cover is composed of sedimentary sequences of Mesozoic and Paleogene age. Colluvial deposits reach a thickness of a few meters in some low order catchments of the range and glacial deposits are found in the upper reaches of the Axial Pyrenees, locally presenting a thickness of several tens of meters.

The climate of the Eastern Pyrenees is strongly influenced by two factors: the vicinity of the Mediterranean Sea and the orographic effects of the Pyrenean mountain range. There are two typical rainfall patterns, which can trigger debris-flow activity (Hürlimann *et alii*, 2003b): i) Short duration, high intensity rainfalls related to convective summer storms, and ii) moderate intensity rainfall during autumn/winter lasting for several days or weeks and affecting large areas.

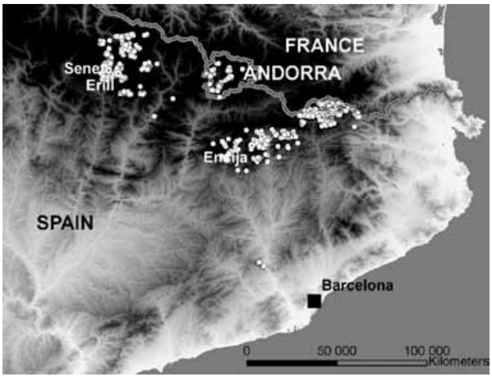

Fig. 1 - Location of the three monitoring stations. White dots show the debrisflow events gathered in the database and used during the site selection

SELECTION OF TEST SITES

As first step, a debris-flow database for the Eastern Pyrenees was built up by the interpretation of aerial photos and the research of different types of publications including technical reports and administration archives. The locations of the debris-flows gathered in this database are shown in Fig. 1.

Then, the activity of selected torrents have been checked by aerial photographs of different years and finally three test sites have been chosen to set up the monitoring system (Table 1). Ensija site is situated in the Pre-Pyrenees, where bedrock mostly consists of marls, conglomerates and limestones that are covered by a periglacial colluvium. The two other sites (Senet and Erill) are located in the Axial Pyrenees, where bedrock consists of slates and the superficial deposits are glacial deposits (tills).

DESCRIPTION OF DEVICES INSTALLED

In Table 2, the principal devices installed in the three monitoring stations are listed. Information and evaluation of the devices available for debris-flow monitoring can be found in several reviews (Itakura *et alii,* 2005; La Husen, 2005; Arattano & Marchi, 2008).

GEOPHONE

Geophones measure the ground vibration generated by debris flows (e.g. Arattano, 2000). In each catchment, four geophones GEOSPACE 20 DX with a natural frequency of 8 Hz and a standard coil resistance of 395 Ohms have been installed. An electronic signal conditioner transforms these vibrations into a number of

	Ensija	Senet	Erill
catchment area (km^2)	0.80	0.70	0.37
Orientation	N	W	SE
maximum elevation (m asl.)	2260	2475	2100
minimum elevation (m asl.)	1745	1350	1310
elevation of sensors (m asl.)	1750-1810	1300-1400	1350-1450
year of installation	2009	2009	2005

Tab. 1 - Situation and general information on the three test sites

	Ensija	Senet	Erill
geophones	4	4	4
ultrasonic device	1	1	0
video camera	0	0	1
ring-net with load cells	0	0	1
meteorological station	1	1	1

Tab. 2 - Number of the devices installed in the three test sites impulses per second (IMP/sec), if a certain threshold of acceleration is exceeded. Therefore, the output data of the geophones provide vibration intensity of the passing debris flow, which can be used to estimate a mean front velocity between the different geophones. In addition, the geophones trigger the other measuring devices installed along the torrent. Geophone data can also be used to determine the moment of debris-flow initiation, which is necessary information in the rainfall analysis.

ULTRASONIC DEVICE

Ultrasonic devices measure the flow depth of a passing debris flow. In two catchments, Senet and Ensija, an ultrasonic device (UC6000-30GM-IUR2-V15 manufactured by Pepperl+Fuchs) was installed. The raw ultrasonic measurements, which depend on the air temperature, are automatically and internally corrected by means of a temperature sensor that is connected to the device. Additional configurations on the longitudinal range of measure, the opening or the numbers of measures could be realised by the program ULTRA3000 provided by Pepperl+Fuchs.

The ultrasonic data in combination with the geophone data can be used to estimate a mean flow velocity and finally a discharge.

VIDEO CAMERA

Video cameras provide very helpful qualitative information on the general flow behaviour. Video or photographic images can also be used for detailed processing (e.g. Chang & Lin, 2007). In Erill, a standard GANZ video camera is installed in combination with a spot light.

METEOROLOGICAL STATION

The meteorological station includes a rain gauge and a thermometer. The rain gauges are standard tipping bucket devices with a resolution of 0.1 mm (RM YOUNG 52203). Because rain gauges are unheated, the temperature data is necessary to distinguish, if precipitation has been rain or snow. The recording interval of both sensors is defined constant as 5 minutes

FLEXIBLE RING-NET AND LOAD CELLS

In Erill test site, a flexible ring VX160 of GEOBRUGG was installed in combination with several load cells of 500 kN capacity incorporated along the horizontal cables. The goal of these devices is to test the effectiveness of such kind of protection measurement. Detailed information on this topic can be found in Luis-Fonseca *et alii* (2011).

LOGGING AND TRANSMISSION OF DATA

Two different clusters of devices can be distinguished in each test site: i) the meteorological station, and ii) the "flow station", which consists of all the other devices installed along a torrent reach (geophones, ultrasonic sensor, video camera and load cells). Both clusters incorporate a datalogger, and a GSM modem for data transmission, all of them powered by a battery which is recharged by means of a solar panel.

The meteorological station is controlled by a Campbell Scientific CR200 datalogger powered by a 12V 7Ah battery connected to a 10W solar panel and also contains a Wavecom Fastrack GSM modem.

The readings from the sensors connected to the "flow station" are recorded in a Campbell Scientific CR1000 datalogger. The datalogger is programmed to control the frequency of sensors scanning and data recording, as described in the following section. The power supply is established by 12V 24Ah battery which is recharged by a 30W solar panel. The video camera is powered separately by an additional battery and a solar panel. Data transmission is completed again by a Wavecom Fastrack GSM modem

Fig 2 - Oblique view of the Senet test site indicating the position of the different devices installed. GEOn: geophone number n. US: ultrasonic ic sensor

DATALOGGER PROGRAMMING

A main characteristic regarding debris-flow monitoring systems is the fact that it should distinguish between a "no-event" mode, when no debris flow occurs in the torrent, and an "event" mode in the case of debris-flow occurrence. This means that an adequate programming of the datalogger is of essential importance. Figure 3 shows a flowchart of the program mounted in the Senet datalogger controlling the four geophones and the ultrasonic device. In "noevent" mode the datalogger scans the four geophones at 1 Hz (1 scan per second) and checks the number of impulses of each geophone. If one of the geophones exceeds the threshold of 20 IMP/sec, the program switches to "event"-mode, herein called "monitoring event".

If no geophone exceeds the defined threshold, the information on vibration and an ultrasonic measurement will be recorded in a "no-event" output file every 5 minutes. In the "event" mode, the four geophones and the ultrasonic device record at 1Hz. After the debris flow passage and the vibrations at the geophones decrease below the threshold of 20 IMP/sec, the system keeps in "event" mode during 2 additional minutes before switching back to "noevent" mode.

DEBRIS-FLOW EVENT IDENTIFICATION

Geophone data include measurements of passing debris flows, but also of other phenomena that induce ground vibration (e.g. rock fall from the steep outcrop of till in the source zone, thunder during a storm, boulder transport by torrential flows or by hyperconcentrated flows). Thus, geophones provide indirect information that must be correctly interpreted. In contrast, the ultrasonic sensor supplies flow depth and, therefore, contributes to the identification of debris-flow. In Senet test site, many "monitoring events" were recorded during the first year test phase. Nevertheless, the ultrasonic sensor was most time not operational due to technical problems and also due to a rockfall that destroyed the device. Thus, geophone data were the principal information for debris-flow identification. However, geophone vibration not only depends on the type of flow process, but also on the properties of the channel bed (e.g. presence of soil or rock, soil thickness, type of soil matrix) and on the distance between the flow and the sensor. Finally, the interpretation of monitoring data was based on both the geophone records and the periodic field reconnaissance looking for morphologic changes.

The first step during the interpretation of the "monitoring events" involved a determination of confidence on the geophone data, which was expressed as a qualitative likelihood. The "monitoring events" were classified in four likelihood categories high, medium, low and null. The different classes were assigned considering the maximum vibration intensity (in IMP/sec), the event duration and the shape of the impulse time-series. Our data and experiences from other studies (e.g. Arattano, 2000) indicate that a mature debris flow seems to give a record with a continuous vibration, a quick-rising and slow-decreasing shape, a minimum duration of ground vibration of at

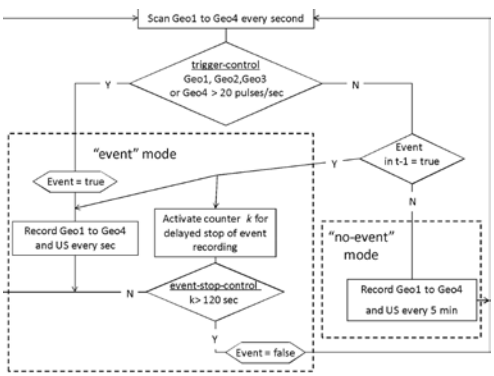

Fig. 3 - Flowchart of the program installed in the datalogger controllinggeophones and ultrasonic device in Senet

Date (dd/mm/yyyy)	Vibration intensity (IMP/sec)	Monitoring event likelihood	Maximum rainfall intensity (mm/h)
07/08/2009	460	high	30
01/09/2009	76	medium	20.5
25/03/2010	160	high	8.7
01/05/2010	99	medium	7.1
10/05/2010	59	medium	5.1
27/05/2010	89	high	3.3*
10/06/2010	51	medium	5.1*
27/06/2010	61	high	8.5
29/06/2010	58	medium	4.3
11/07/2010	244	high	49.3
21/07/2010	263	high	11

Tab. 3 - Summary of maximum geophone vibration intensity and corresponding likelihood of selected monitoring events at Senet test site. Maximum rainfall intensity related with the events is also indicated least some tens of seconds and a peak greater than 50 IMP/sec. Additionally, a progression of the vibration down the channel should be recorded by the different geophones. Finally, we also incorporated the information gathered during the periodic controls focussing on geomorphologic changes in the field. This field controls have especially been used to support events of high likelihood.

PRELIMINARY RESULTS

In the following, three different types of data will be described, all of them focussing on the Senet test site. First, a summary of selected monitoring events recorded at the Senet site is presented. Second, detailed data of three specific cases will be shown. These three events were on one side classified as a high likelihood (Tab. 3) and on the other side the geomorphologic changes in the field indicated that a debris flow has occurred. Third, the analysis of the rainfall data will be described focussing on triggering conditions for debris flows and analysing different rainfall thresholds.

During the first year test phase between August 2009 and July 2010, a total amount of 280 “monitoring events” have been gathered, although many are clearly false alarms corresponding to null-likelihood events (events with duration of one or two seconds). In fact, after the initial filtering of these “monitoring events” only 23 events could be classified with a likelihood higher than null. This means that almost three events per month could be registered from August to October 2009 and from March to July 2010. These events were subsequently analysed more in detail and classified with low, medium or sure likelihood.

Table 3 shows that 6 events could be classified with high likelihood, 6 with medium and 11 with low likelihood. The long distance to the Senet test site (which requires a trip of two days) and the high frequency of monitoring events hindered to carry out a field inspection after each event. That’s why monitoring events of medium and low likelihood could not be directly checked by a field inspection

Although this classification of the events in different likelihood categories involves many uncertainties, some general patterns on the measured ground vibration could be observed. Two conclusions can be done regarding the maximum intensity. First, events characterised by high likelihood generally correspond to monitoring events with maximum intensities greater than 80 IMP/sec. Second, events of medium likelihood showed usually intensities greater than 40 IMP/sec..

In spite of all these drawbacks that have occurred during the first year test phase, the summary of events listed in Table 3 indicates that the Senet test site is characterised by a rather high debris-flow activity.

EXAMPLES OF DEBRIS-FLOW EVENTS RECORDED IN THE SENET MONITORING SYSTEM

SENET: AUGUST 7, 2009

Just 2 weeks after installation of the monitoring system, a first debris flow was recorded at Senet. At that moment, a preliminary version of the datalogger program was running and only two geophones (GEO1 and GEO4) were operational. Nevertheless, interesting data and new experiences to improve the monitoring system could be gathered.

The recorded data on rainfall, ground vibration and flow depth are shown in Fig. 4. Geophone and ultrasonic measurements indicate two main peaks. These peaks could be interpreted as two main debris-flow surges and are clearly correlated to two peaks in the rainfall intensity. The rainfall was a typical convective summer storm and lasted about 5h. The total rainfall amount was about 75 mm, but a clear maximum in-

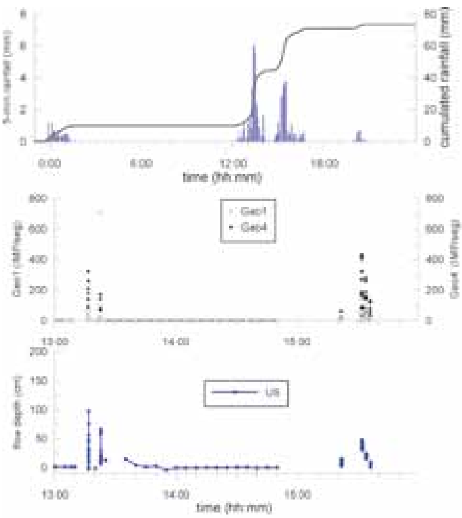

Fig. 4 - Rainfall, geophone and ultrasonic device data registered during the Senet debris flow on August 7, 2009

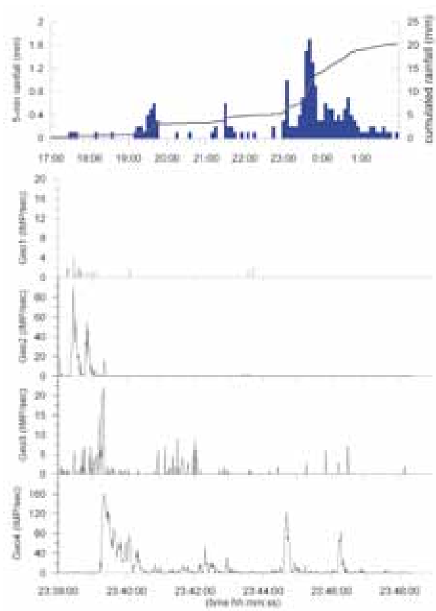

Fig.5 - Rainfall, and geophone data registered during the Senet debris flow on March 25, 2010. Watch different axes for the geophone data

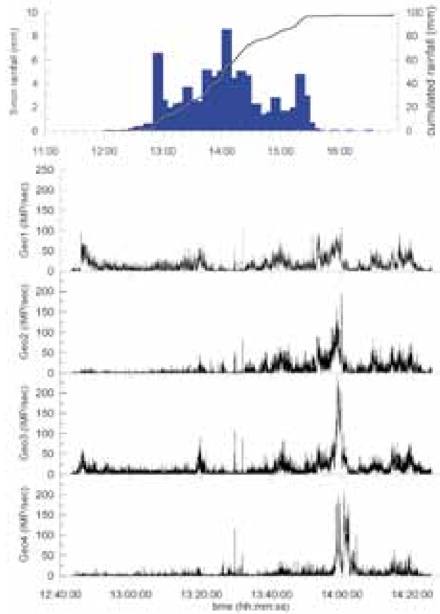

Fig.6 - Rainfall, and geophone data registered during the Senet debris flow on July 11, 2010

tensity of about 6 mm/5min or 30 mm/h could be observed around 13:30. Regarding the geophone and ultrasonic data, no approximation of mean flow velocity between the devices could be done and especially the measurements of flow depth may represent underestimated values, because the defined recording frequency of 10Hz (one record per decisecond) was leading to some malfunction in the data gathering.

SENET: MARCH 25, 2010

An important debris-flow event with a volume of about 2000 m3 was recorded at the end of March 2010. A rainfall with a small total amount of about 20 mm and a low intensity of less then 2 mm/5min and about 8.7 mm/h triggered this rather important event (Fig. 5). A major increase in temperature during the 10 days preceding the debris flow support the hypothesis that snowmelt may have played a significant role in the initiation mechanisms. This aspect was the topic of another analysis (Hürlimann *et alii*, 2010) and will not be discussed herein.

Finally, the rainfall causing the debris flow was characterised by a low intensity and by a duration of several hours, which represent a common pattern for rainfalls occurring during spring season in Eastern Pyrenees. The debris flow took place around midnight and temperature was between 4-6 ºC. The ground vibrations produced by the debris flow lasted from ~1 minute at Geo1 and Geo2 to ~8 minutes at Geo4 and illustrate interesting information on the flow behaviour (Fig. 5). The quality of the data differs for each of the four geophones, but especially geophone 4 (Geo4) shows a sharp increase of the vibration intensity with a subsequent continuous decrease. This shape represents the debris-flow front with maximum discharge and maximum concentration of boulders and stands for a common feature in debris-flow behaviour (e.g. Arattano, 2000).

Vibrations gathered by three geophones (Geo2, Geo3 and Geo4) include a peak and thus some preliminary velocity estimates could be carried out. The resulting mean velocity of about 3 – 5 m/s is rather low and can only be explained by a stop-and-go mechanism. No ultrasonic device measurements could be gathered, because a previous rockfall destroyed the steel cables that fixed the sensor.

SENET: JULY 11, 2010

A rather different debris flow occurred in the afternoon of July 11th 2010. The registered ground vibrations lasted almost three hours from 12:43 to 15:23 and several surges represented by maximum

Fig.7 - Morphologic changes in the higher part of the Senet fan caused by the debris flow occurred on July 11th 2010 (left: before and right: after the event)

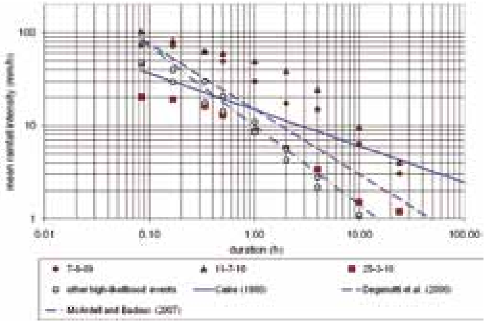

Fig.8 - Critical rainfalls recorded at Senet test site during the first year test phase (only the events related high likelihood are illustrated). Three different thresholds are added for comparison

values of impulses per second can be observed (Fig. 6). The ground vibrations perfectly coincide with the duration of the rainfall measured (about three hours). The rainfall pattern represents the characteristics of a short convective storm. The total rainfall registered was 97.6 mm and the maximum intensity was about 9 mm/5min and 49.3 mm/h. The largest detected ground vibrations were observed at about 14:00 coinciding with the highest rainfall intensity. The field reconnaissance carried out 8 days after the event showed great morphologic changes (channel erosion in some sections and accumulation in other ones, see Fig. 7).

In contrast to the spring event shown in Fig. 5, all the geophones registered high vibration intensity. The explanation that even the geophone 1 (Geo1) reflected this time high ground vibration, was a change of the flow path. During the July event, the debris flow passed much closer at Geo1 reducing the distance between the moving sediment and the sensor, which consequently produced an increase of the ground vibration. Such alterations of the flow paths reducing or increasing the distance between channel bed and sensor are important facts that should be taken into account during the setup of a monitoring station or a warning system.

Again, an approximation of the mean flow velocity between the geophones Geo2, Geo3 and Geo4 has been carried out using the data of the peak at about 14:00. Finally, velocity estimates between 3 and 4 m/s could be calculated, which again represent rather low values for a granular debris flow along a channel bed with a slope of about 20º.

RAINFALL TRIGGERING CONDITIONS

Empirical rainfall thresholds are a common tool in the research of rainfall-triggered slides and debris flows and can be established using statistic analysis of historic data (e.g Guzzetti *et alii*, 2007). There are different types of thresholds, but the most common is the one proposed by Caine (1980) comparing rainfall duration and mean intensity.

The definition of such a rainfall threshold for debris-flow initiation in the Eastern Pyrenees is one of the main objectives of the three monitoring systems installed in the region. The data gathered during the test phase of the observation stations provide first important information on the rainfall conditions triggering debris flows, but do not yet allow the determination of a reliable threshold. In the following, precipitation data are again related to the Senet test site, since most of the information has been gathered at that monitoring station. In this preliminary analysis, only the rainfall data associated with monitoring events, which have been classified as medium and high likelihood for debris-flow occurrence, are taken into account (Fig. 8).

A first conclusion regarding the general rainfall pattern indicates that most of these monitoring events were triggered by short duration-high intensity rainfalls. However, other events were related to moderate intensity rainfalls and the one at the end of March 2010 probably associated with antecedent snowmelt. The different rainfall data gathered at Senet can be compared with other thresholds published. No comprehensive rainfall threshold has been established for debris-flow occurrence in the Eastern Pyrenees and only some very general criteria for landslide initiation have been published (Corominas & Moya, 1999; Corominas *et alii,* 2002). Finally, three thresholds were selected for comparison with the Senet data: i) the threshold defined for the debris-flow monitoring station installed at Illgraben (McArdell & Badoux, 2007; Badoux *et alii,* 2009), ii) the threshold established for the Moscardo test site (Deganutti *et alii,* 2000), and iii) the well-known global threshold defined by Caine (1980). The rainfall events that triggered event classified with high likelihood (see Tab. 3), are generally fitting the three threshold conditions. However, the debris flow occurred during spring 2010 is clearly situated below the critical rainfall amount, which supports the hypothesis that an additional water input may have been available and that snowmelt may have played an important role in the initiation of that event.

The conclusion of this preliminary analysis of the critical rainfalls indicates that different thresholds must be established for such kind of debris-flow triggering.

CONCLUSIONS

During the selection, the configuration and calibration of the different devices and also during the set-up and testing of the monitoring system many experiences could be gathered that will be subsequently discussed. These comments may help other research groups interested in debris-flow monitoring to build up a new system or to improve an existing one.

Most of the problems regarding the device configuration have been related to electronic tasks. In particular, the electronic schemes controlling the geophone signals are rather sophisticated. Moreover, the selection of the resistor value at the conditioner of the geophone signal, which defines the critical acceleration to initiate the impulse count, is of great importance. This value depends on several factors such as underground lithology or the distance to the torrent, all of them related to the damping of vibration.

A first version of the datalogger program included a registering frequency in the "event" mode of 10Hz for the geophones and the ultrasonic device. Recorded data, however, showed that such a frequency was exceeding the capacity of the devices installed.

Additional problems have been related to the power supply, because not enough sunshine was available to charge the battery during autumn. So, larger solar panels and batteries have been installed subsequently.

Another unexpected problem arose from the rockfall occurrence in the Senet site. Several rockfalls including large granitic boulders failed out of the glacial deposit and caused considerable damages at some monitoring devices located in the higher part. One rockfall of unexpected volume even destroyed the ultrasonic device situated initially near the geophone GEO2 position. Both the ultrasonic device and the meteorological station were dislocated down into an area not affected by rockfalls. Minor damages had to be accepted by vandalism and animal activity.

Finally, a major problem was the correct interpretation of the geophone data. False alarms due to triggers not associated with fluvial processes could be identified easily, but an accurate distinction between different processes such as debris flows, hyperconcentrated flows or sediment transport was difficult. Thus, all the events monitored during the test phase were classified into different likelihood categories applying the approach previously explained. However, an improvement of the visual control in test sites with high activity is unavoidable. Therefore, in the Senet test site, a high-resolution video camera MOBOTIX M12D-Sec DNight D43N43 was set up in August 2010. The installation of a video camera is considered as very helpful or even fundamental to improve the analysis of the monitored debris flows. Image analysis from video camera records will also contribute to resolve uncertainties on flow velocity estimates and doubts on the flow behaviour.

In spite of the problems encountered during this test phase, several conclusions can be obtained. Monitoring results of the first year show that the Senet test site situated in the Axial Pyrenees is characterised by high activity. On one side, abundance of debrisflow prone material and high slope angles in the initiation zone, which consists of a thick till deposit, create perfect conditions for debris-flow initiation. On the other side, frequent convective rainstorms are common in this high-mountain area. However, not only convective summer storms have triggered debris flows in Senet, but also a combination of moderate to small rainfall with snowmelt in early spring.

In contrast, only minor debris-flow frequency could be observed in the Ensija and Erill test sites. The explanations of this are rather different. In Ensija, the sediment availability is more limited due to the colluvium layer and only large rainstorms seem to generate debris flows. In Erill, the initiation area is similar as in Senet, but the bed slope of the channel is much lower.

The experiences gathered at the three test sites show that debrisflow monitoring is a complex and difficult task including many research areas. Apart from the typical research fields like hydraulics and geomorphology, also areas like geophysics, electronics, telecommunications etc. are necessary. Especially electronic skills are essential for a correct set-up and calibration of all the devices and sensors.

The major conclusion obtained during the test phase is the fact that debris-flow monitoring only with geophones and ultrasonic devices is possible, but can not provide enough data for a thorough analysis of the flow behaviour. That's why a video camera is recommended in test sites with rather high activity.

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