DEBRIS-FLOW PROTECTION IN RECURRENT AREAS OF THE PYRENEES. EXPERIENCE OF THE VX SYSTEMS FROM OUTPUT RESULTS COLLECTED IN THE PIONEER MONITORING STATION IN SPAIN

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ABSTRACT

The south eastern part of the Pyrenees is currently affected by debris flow phenomena. The combination of Mediterranean and Continental climate, the orography (up to altitudes of 3300 m), the glacial materials on the slope's surface, the lack of arboreal coverage compared with the rest of the Pyrenees, the high seismicity and the increasing human occupation in the valleys, put altogether is a very dangerous combination and makes the debris flow management extremely difficult. The first monitoring system for debris flow phenomena was installed in Spain in 2005. The aim was to monitor the debris flow phenomenon's behaviour in the Erill basin, in the north of the province of Lerida. The Erill location in the south of the Pyrenees is one of the places where the debris flow phenomenon is common and where, apart from the possible magnitude of any event, the likely affected area includes the urban area of the Erill village. Remote controlled autonomous monitoring equipment was installed in this location. It was composed of an automatic meteorological station, a set of geophones to activate the measuring and recording systems, a VX160 barrier protection system, monitored with load-cells, a camera and digital recording equipment, all connected to a data logger with a GSM modem. The information provided by the detection system was completed during 2009 by a topographic schema, created by the LIDAR system, of the basin that generates the debris flow. The objective was to try to detect, before the event, the specific deformations that cause the debris flow. We have collected information related with different events of small volume (< 100m³) that had a direct correlation with the intensive rainfall in the basin. During 2009, based on the knowledge gained from the behaviour of the Erill basin, the first applications and designs of VX160 systems were created for other sites. The work done in the Portainé gully is an example of this. In 2008, this zone was affected by a debris flow of more than 20.000 m³. The protection system that was installed was made up of 9 VX160 transversal protection lines, with a total retention capacity of approx. 25.000 m³. Three months after they were installed, the fences were completely full as a result of two events caused by summer storms. The installed solution costs 40% less than the traditional check dam solution. This paper shows the importance of the research, of these specific phenomena in the Pyrenees, to the development of protection technology. The autonomous measurement equipment, together with the tested protection system can be applied, with the corresponding reduction in costs, to civil protection and hydrological correction situations in urban and suburban zones where debris flow is a recurring phenomenon.

Key words: *monitoring, hydrological correction, debris-flow protection, Pyrenees, ring net*

INTRODUCTION

Potentially dangerous events are part of the normal dynamics of natural systems. Daily interaction

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with human activity generates increasing losses, that's why management is essential. Reports on natural disasters created by the United Nations International Strategy for Disaster Reduction (ISDR) and by large insurance companies conclude that the social and economic impact of natural hazards, both in developed and developing countries has been increasing over recent years and shows the same trend for the foreseeable future. The causes are attributed to the severity of natural phenomena, together with the physical and social vulnerability of the territory. Several papers suggest that the vulnerability factor has increased alarmingly.

In general, the lack of reliable and comparable data makes it impossible to develop a detailed picture after the event, which would be extremely useful, both for technical and scientific studies on the extent of the phenomenon, and for the authorities responsible for mitigating its effects. Field experience in the design and location of flexible systems is still limited due to the frequency with which these phenomena occur and the uncertainty associated with the extrapolation of results from laboratory to full scale events. In 2005, with the support of the Swiss Federal Agency for the Promotion of Innovation (KTI), a field trial was commissioned in order to evaluate the performance of the flexible ROCCO® ring net against debris flows (Fig. 1).

Traditional measures of mitigation against debris-flow have consisted of the construction of expensive concrete dams or strong steel structures to retain the sediment. The VX-UX flexible systems of ring net barriers provide a new lower-cost alternative and have already been successfully used for flows of up to 25,000 m^3. The aim of this paper is to present the application of this technique in areas affected by debris

Fig. 1 -- Evolution of debris-flow event. Experience in Illgraven (Switzerland)

flow events while documenting the performance and optimizing the design procedures using results from the natural scale on-site tests.

GENERAL SETTING

The Pyrenees is the large mountain range that separates Spain and France and also is home to the country of Andorra. It ranges from east to west and reaches an altitude of 3000m, with a combination of igneous, metamorphic and sedimentary materials, amongst which we highlight the glacial and a very important condition of two major orogenies: the Ordovician and Alpine. These two orogenies produce discontinuities and the combination of these discontinuities creates instability problems. Together with other areas, the eastern Pyrenees was severely affected by flooding in November 1982 (GARRIDO, 1992). Significant human and economic losses have required detailed defence projects and hydrological correction, which are still being implemented in the region.

The measures used have generally been the construction of check dams across the flow of the streams that were most severe in 1982 using either a stone, concrete or metal structure or any combination of the three materials. These projects inherited the calculation-design, implementation and construction methodology of structures designed in the Pyrenees in the late nineteenth and early twentieth century. The traditional techniques applied in modern times have had a significant economic and environmental cost.

Research carried out since 2001 by WSL and GEOBRUGG AG in Switzerland (AMMANN & VOLKWEIN, 2006), at the debris-flow test field, has greatly advanced the concept of design and operation of protective measures against debris flow, with the knock-on effect in the applicability of the designs.

In 2005, as a result of the research agreement between the Forest Technology Centre in Catalonia, Forestal Catalana and Geobrugg Ibérica, testing of the VX-UX systems developed by Geobrugg AG (ROTH, 2003) began in particularly active basins in the Pyrenees Mountains and the Coastal Mountain Range. Two test sites were installed in the La Galera and Erill gully (LUIS FONSECA *et alii,* 2006), in order to compare the effect of debris-flow phenomenon in two different environments: the Axial Pyrenees and the Mediterranean Coastal Range. The data collected so far has already led to the design and construction of effective

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protections which have low economic and environmental costs such as the Portainé gully.

ERILL TEST SITE AND PORTAINÉ GULLY SITE

The Erill site in the Pyrenees was selected as a Test Site due to its well known high debris flow activity. While the most significant volumetric events have coincided with other major events in this region, its constant economic activity has resulted in important investment which has not eliminated the risk of further debris flow. This is a very small basin (<0.5 km^2) with a pronounced slope incline (>16º), with almost no plant coverage due to the continued erosion and loam sediment and gravel-loam deposit of glacial origin that lies on slate and Devonian quartzite. These conditions are applicable to many other basins in this area (Fig. 2).

The Portainé gully has been one of the most active in the Pyrenees since 1982 where it is estimated, based on the incisions and retrospective measures and simulations carried out, that over 50,000 m^3 has been displaced. In 2008, the access road to the ski resort was destroyed and the Hydroelectric Station, was significantly damaged, by the movement of more

Fig. 2 - Profile overview of the Erill test site

Fig. 3 - Profile overview of the Portainé Job Site

than 20,000 m^3 (PORTILLA *et alii*. 2010). In 2010, after the installation of nine VX type protections, two events that coincided with summer storms caused the accumulation in the barriers of more than 25,000 m^3. The basin has its highest point in the Orri Mountain, at an altitude of 2439 m, with its lowest point flowing into the Romadriu gully, at an altitude of 950 m, implying a variation of almost 1500m in about 5.7 km with an average gradient of 16º, with some places surpassing 26º in the steepest points (Fig. 3). This is a watershed covered by grass above 2100 m, while the rest is covered with trees and native shrub vegetation. Geologically, it is formed by metamorphic materials, quartzite and slate in general, with a very important fragmentation, which favours a sediment cover that is aligned with the gradient slope.

DESCRIPTION OF DEVICES AND PROTECTION SYSTEMS
ERILL TEST SITE

In the Erill gully in 2005 a set of auscultation equipment was installed, the combination of data extracted should allow a betterunderstanding of the correlation between local hydrology, local geology and development of the event. A prototype of the VX barrier was also installed, in order to retain the debris-flow. The

installation included a video camera in order to monitor the events. In the spring of 2010 a LIDAR topography scanner of the basin has been realized, to detect possible premonitory deformations of mass movements and to compare volumes displaced by each event. Additionally wireless strain gauges were installed over support ropes of the VX flexible structure. For next year, it is planned to implement a set of string piezometers to determine the degree of saturation that exists before the mass movements (Tab. 2).
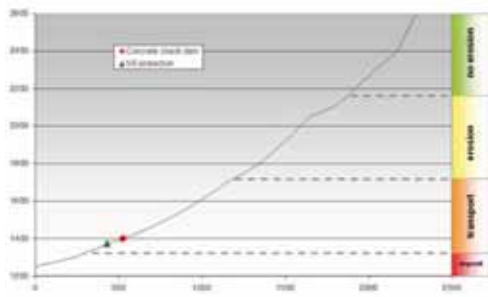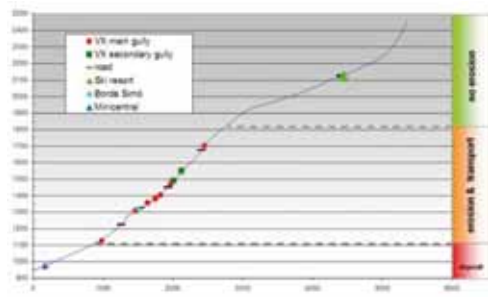
PORTAINÉ GULLY

In the Portainé gully, eleven VX protections were projected to be installed in 2009, in order to prevent

ERILL monitoring equipment	2005	2010	next
Geophones	4	0	0
Video-camera	1	0	0
VX barrier system	1	0	0
load cells	0	4	0
automatic meteo-station	1	0	0
LIDAR topographic measurement	0	1	1
piezometric cells	0	0	4
Webcam control	0	1	0

Tab. 2 - Devices installed in Erill test site

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future damage similar to that caused in 2008. In the winter and spring of 2010, nine VX protections of the eleven planned were installed (Tab. 3 and 4). The basic objective was to gradually retain the material provided by the potential debris-flow events, creating a mid-term hydrological correction. The works associated needed to ensure minimal environmental impact, such as the prohibition to open access paths during the installation. The client also requested that the works maintained the fluvial dynamics characteristic of a high mountain torrent river and that it should be useful only for catastrophic events.

JULY 22ND EVENTS. PRELIMINARY DATA

Since the installation of the auscultation system in the Erill gully, there have been several episodes of debris-flows, but without doubt the one that occurred on July 22nd, which affected within minutes of each other the Erill basin and the Portainé gully, has marked an important milestone in our research. The arrival of cold wind at altitude from the north and warm wind pushed from the east is symptomatic of a volatile weather pattern, with the potential for heavy localized rains (Figg. 4 and 5). Therefore the forecast is for a summer storm in the Pyrenean area

An evening summer storm progresses from west to east reaching the Erill gully (Figg. 8 and 9) at 19:00 hours. At 20:38 a warning system was activated automatically sending a signal, to our call centre operations, via GSM "Debris-Flow in Erill". The same

storm reached the Portainé gully one hour later. According to eyewitnesses an impressive debris-flow event cut the access road to the ski resort of Portainé at 22:30 hours. The Erill's auscultation system recorded an event for a period of 17 minutes. The record shows
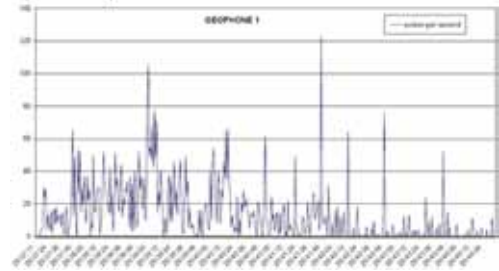
Fig. 4 - *Rainfall data registered in Erill's debris flow on July 22nd.*
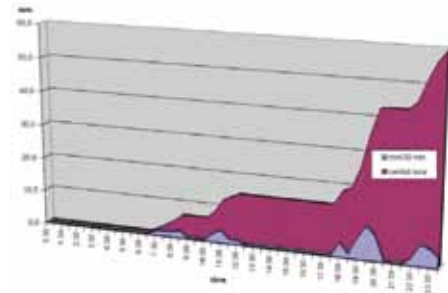
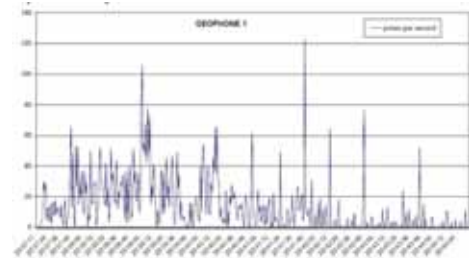Fig. 5 - *Rainfall data registered in Portainé's debris flow on July 22nd*

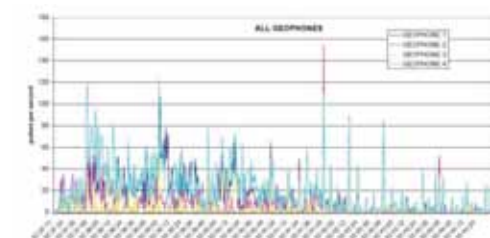Fig. 6 - *Geophone data registered in Erill's debris flow on July 22nd.*

Fig. 7 - *Geophone data registered in Erill's debris flow on July 22nd*

Portainé monitoring equipment	2010	next
Geophones	0	4
Video-camera	0	1
VX barrier system	9	2
load cells	0	22
automatic meteo-station	1	0
LIDAR topographic measurement	0	1
piezometric cells	0	1
Webcam control	0	1

Tab. 3 - *Devices installed and position in Portainé test site*

m asl.	position	Barrier Type	Height (m)	Width (m)
1.470 m	G-1	VX-160	5	20,0
1.490 m	G-2	VX-160	4	27,0
1.550 m	G-2	VX-160	4	26,0
1.700 m	G-1	VX-160	6	19,5
1.405 m	G-1	VX-160	4	13,5
1.380 m	G-1	VX-160	5	11,5
1.355 m	G-1	VX-160	5	13,5
1.308 m	G-1	VX-160	4	16,8
1.125 m	G-1	VX-160	4	13,5

Tab. 4 - *.Devices installed and position in Portainé test site*

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(Figg. 6 and 7)

- different flow waves evolve through the channel auscultation by 4 geophones.
- the high current flows recorded in geophone 1 are less evident when they get to the position of the VX system where the geophone number 4 is located.
- a constant background vibration is recorded by all the geophones once the event reaches the position of geophone number 1.
- the geophone number 4 installed in vertical section of the VX barrier, recorded impulses by the effect of vibration of the flexible protection system itself.

The event caused a build-up in the VX system of 680 m^3. Trial pits carried out in the sediment and sedimentary structures showed that 320 m^3 was caused by hyperconcentrated flow, while the rest of the materials have been transported by turbulent flow and turbulentlaminar.

Although at the time of the event the load cells were not installed due to maintenance-related issues, a calculation has been made from the experimental data at our disposal with brake rings and ring nets, in which we can measure plastic deformation (Figg. 10-11) in the constituent elements of the VX system and convert them to load measurements.

At the same time, one of the largest debris-flow events in the Pyrenees was happening. Nine VX flex-

Fig.10 - *Energy absorption of the single brake rings*
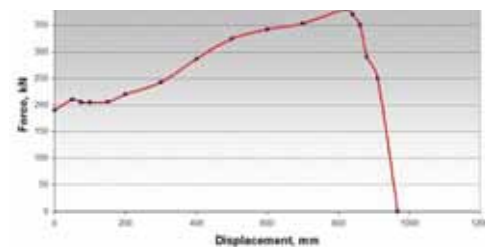
Fig. 11 - *Force-path diagram for the breaking rings*

Fig. 8 - *Frontal view of the barrier filled in Erill*

Fig. 9 - *Lateral view of the barrier filled in Erill*

Fig. 12 - *Pictures of a VX in the Portainé gully before and after the event*

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ible structures were filled (Fig. 12) and exceeded by a debris flow of approximately 25,000 m³. The design of the protection system was based on data obtained from the last event recorded and registered in Portainé in mid 2008.

It was made with the VX-160 model with heights of between 4 and 6 meters.

In the same way that was done for the Erill gully, we can determine the energy consumed by each of the fences and the entire hydrological correction system as a whole, implemented in the Portainé gully.

With the topography records taken three months earlier, during the construction of the fences, an accurate comparison could be made of the volumes held by the VX protections (Fig.13).

Due to the fact that the volume of mobilized material is known and that we have a good knowledge of the upwelling zone and/or erosion of the contributions, them we can make an accurate calculation of the energy generated by the event.

PEACH DISCHARGE

Several studies proved that the peak discharge of a debris flow is correlated to its volume. There are
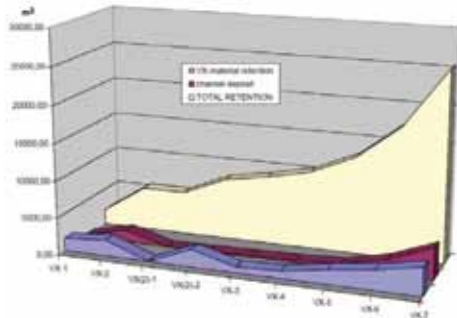
Fig. 13 - Lateral view of the full VX system and graphic with the total material retention in the Portainé gully after the 22nd July event

different relations for granular debris flows and mud flows. MIZUYAMA *et alii* (1992) propose for a granular debris flow (debris avalanche) the following empirical relationship between peak discharge and debris flow volume:

$$Q_P = 0.135 \ V_{DF}{}^{0.78} \qquad (1)$$

where: Q_P: flow peak discharge, V_{DF}: average volume of the material The following equation represents the corresponding relationship for mud flows:

$$Q_P = 0.0188 \ V_{DF}{}^{0.79}$$

DETERMINATION OF FLOW VELOCITY

By using the peak discharge it is possible to estimate the average flow velocity v at the front of the flow. RICKENMANN (1999) proposes a regime condition for the relation between velocity, peak discharge and slope inclination (friction considered). S refers to the gradient of the torrent (tangent of the slope inclination in degrees).Typical values are S=0.18 (10°), S=0.36 (20°) or S=0.58 (30°).

$$v = 2.1 \ Q_P{}^{0.33} \ S0.3^3 \qquad (2)$$

Japanese guidelines (MURAISHI, 1997) suggest a Manning- Strickler equation to determine the average flow velocity nd refers to a pseudo-manning value which is typically between 0.05 s/m$^{1/3}$ and 0.18 s/m$^{1/3}$, while the values for granular debris flows lay between 0.10s/m$^{1/3}$ y 0.18 s/m$^{1/3}$. We could also arrive at this conclusion using literature such as the one below; in this case we know the maximum slope of the course (26º) in the area where the VX barriers have been installed.

$$v = 1/ \ n_d \ H^{0.67} \ S^{0.5}$$

The flow depth H is calculated by using the cross section and the peak discharge.

n_d is the Manning coefficient, the value is between 0.05 s/m $^{1/3}$ and 0.18 s/m $^{1/3}$

$$H = Qp / v \ b.$$

It's recommended to use both equations and compare the results.

ACTIVE MASS OF MATERIAL MOVED BY THE FLOW

As a result of the composition of the flow and the permeability of the barrier, a wash occurs during the impact; therefore not all the mass that is in the flow is stopped. The actual weight is determined under the assumption that only this part of the flow works dynamically and that the debris barrier is filled with debris

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between the moment of contact and the time when the maximum deflection of the ring net occurs.

The density γ_{DF} of the material is based on empirical values and is about 18-23 kN/m³. The material being moved is usually heterogeneous and of variable density, which can be taken as an average value measured 22 kN/m³ as density.

As a result of the dewatering of the debris flow during the impact on a permeable barrier not all the mass that is in the flow is stopped, but only a relevant length or mass. The relevant mass M_{DF} is determined as follows: It's assumed that only this part of the flow is acting dynamically and that the debris barrier is filled with debris between the moment of contact and the time when the maximum deflection of the ring net occurs. In the Oregon tests (DE NATALE *et alii*, 1996) with volumes of 10 m³ the Timp was about 1s. Real debris flows are expected to be much larger and therefore the braking time will also last longer. Timp is estimated to be between 1 s and 4 s.

$$T_{imp} = 1s - 4s$$

(depending on velocity and barrier length)

In this case the selected value is 1s

The relevant mass is consequently calculated as follows:

$$M_{DF} = \gamma_{DF} \cdot Q_{DF} \cdot t \qquad (3)$$

IMPACT LOADING

With the values of active mass and velocity, we can determine the kinetic energy of the flow in contact with the barrier. The total energy is determined by using the law of kinetic energy.

$$E_K = 0.5 \cdot M_{DF} \, v^2$$

Also, as a result of testing and experience in different locations, it is known that the maximum deflection is reached in the order of 2- 4m. Thus we can estimate the quasi-static load to be borne by the barrier:

According to Newton's second law:

$$F = M_{DF} \cdot a \qquad (5)$$

The distance is obtained from the product of the speed and time

$$D = v \cdot t \qquad (6)$$

Speed is the product of acceleration and time

$$V = a \cdot t \qquad (7)$$

From (6) and (7) it obtains:

$$a = v^2/d \qquad (8)$$

Using equations (4), (5) and (8) we can deduce that the quasistatic force is equal to twice the kinetic

energy divided by the breaking distance

$$F_{QS} = 2 \cdot E_K / d \qquad (9)$$

where:

F_{QS}: quasi-static force;

E_K: kinetic energy;

d: maximum deflection.

It is recommended to multiply by a safety factor to calculate the maximum expected force for the flow of detritus.

$$F_{max} = F_{QS} \cdot FS \qquad (10)$$

FS: Safety Factor, default 1.5

With these combinations of values of kinetic energy E_K and maximum force F_{max} the following results have been obtained (Fig. 14 and 15):

CONCLUSIONS AND OUTLOOK

The need for protection against debris-flow phenomenon in the area of the Pyrenees is growing considering the frequency and strength with which they are hitting the urban and suburban areas in the last decade.

The combination of topography, sparse vegetation, extreme weather and lack of regional planning are parameters that, combined together can create a very dangerous area. The investigation on the debris-flow

Fig. 14 - ROCCO® ring net and the braking elements, in the Portainé Torrent after the 22nd July event

phenomenon that recently began in the Pyrenees is providing important data for the determination of parameters which can be triggers for different areas of study.

The knowledge of critical parameters should enable us to clarify the protections' requirements (main forces at the anchorage points and in the ring net). It should also allow the design and proper use of new technology. The new VX concept clearly implies the transmission of traction forces on the side of the river, the reduction of the water pressure on the flexible structure and has the additional advantage of improved environmental integration.

However, experience shows that it is very important todistinguish in the design phase between the ba sins - debris-flowgenerating areas created as a result

of a landslide and those created from excavation in the riverbed itself, since the design of protection may be significantly different.

VX Systems has demonstrated its support bearing capacity to provide support when faced with loads of up to 25,000 m³ from combined events.

ACKNOWLEDGEMENTS

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