

# Twenty-five years of Vallcebre landslide monitoring: from theodolite to Radar

Josep A. Gili<sup>1</sup>, Jose Moya<sup>1</sup>, Jordi Corominas<sup>1</sup>, Michele Crosetto<sup>2</sup>, Oriol Monserrat<sup>2</sup>, Guido Luzi<sup>2</sup>

<sup>1</sup> Dept. of Geotechnical Engineering and Geosciences. Technical University of Catalonia. Jordi Girona, 1-3 (module D2), E-08034 Barcelona, Spain, j.gili@upc.edu

<sup>2</sup> Remote Sensing Department, Geomatics Division, CTTC, Av. Gauss, 7, E-08860 Castelldefels (Barcelona) Spain.

**Abstract** – In this contribution we present the work carried out for monitoring the displacements of Vallcebre landslide (Eastern Pyrenees, Spain) between 1987 and 2012. The landslide, which extends over an area of 0,8 km<sup>2</sup> and involves more than 20 million cubic meters, has experienced displacements as large as 1 m per year in some points. It has been periodically monitored since 1987, using a wide range of surface and in-hole techniques, successively: triangulation with theodolite, Terrestrial Photogrammetry, Electronic Distance Measurement, GPS, inclinometers, wire extensometers, piezometers, DInSAR and GBSAR. The results using the new techniques have been compared with those obtained with the GPS and the wire extensometer, and checked against fixed stable points. From this comparison, we conclude that even though wire extensometers and inclinometers may have the highest precision, in practice all the systems have their own role in providing meaningful data for the monitoring at different study stages. After the evaluation of the precision and advantages of the different methods, the complementary use of some of them is strongly recommended.

## I. INTRODUCTION

The Vallcebre landslide is located in the Eastern Pyrenees, approximately 125 km north of Barcelona, Spain. Its situation, geological context and complete geomorphological description can be found in [1]. The mobilised material consists of a set of shale, gypsum and claystone layers gliding over a thick limestone bed. The average slope of the landslide is about 10°. The landslide is 1200 m long and 600 m wide, involving an area of 0.8 km<sup>2</sup>, which shows superficial cracking and distinct ground displacements. The landslide is a translational slide with a stair-shape profile. Figure 1 shows a geomorphological sketch of the landslide and the location of the monitored points and boreholes. The most active area is the lower unit, whose toe is being eroded continuously by the Vallcebre torrent. As in most landslides, its structure and behaviour are not simple.

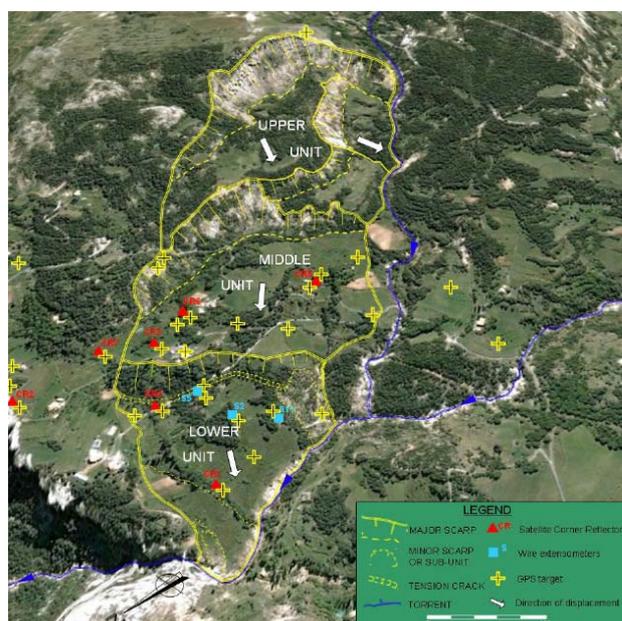


Fig. 1. Geomorphological scheme of the Vallcebre landslide superimposed over an aerial image. The upper, middle and lower units, separated by scarps, can be appreciated. Several GPS, corner reflector and wire measuring points are marked with symbols.

The measurement of displacements is very often the simplest way to observe the evolution of a landslide and to analyse either the kinematics of the movement, the response to the triggering conditions (e.g. rainfall) or the efficiency of corrective measures.

A variety of measuring techniques have been developed to track the movements of unstable areas (see i.e. [2, 3]). Several of these methods have been used in Vallcebre since 1987, beginning with “classical” surveying and photogrammetry, and using GPS from 1995. In 1996, this site was included in the frame of the NEWTECH Project funded by the European Commission. Between July 1996 and March 1997, 14 boreholes were drilled in the slope and equipped with inclinometers, wire extensometers and open standpipe piezometers.

In 2004-2005 multipoint piezometers were installed in three additional boreholes. Later, the Vallcebre landslide was included in another EU-FP7-funded research project known as SAFELAND. In 2007 seven artificial radar corner reflectors (CR) were installed to test the DInSAR monitoring capabilities. In 2010-2011, still within the SAFELAND project (which ended in 2012), the lower part of the landslide was monitored using a Ground-Based SAR (GBSAR). In this sense, the Vallcebre landslide can be considered to be a real-scale laboratory where the performance of different monitoring techniques can be assessed and compared.

In section 2 the measuring systems are described. In section 3 some results are presented and compared in terms of precision and repeatability. Finally, some conclusions are outlined regarding the advantages and drawbacks of the systems in use in Vallcebre. This comparison has been done in terms of cost, ease of use, precision and continuity of the results.

## II. MONITORING SYSTEMS USED IN VALLCEBRE

A summary of the monitoring systems used consecutively from 1987 to 2012 in Vallcebre is given here. More details can be found in [1, 4, 5, 6, 7]

### A. Terrestrial photogrammetry

The first monitoring network established on the landslide was based on terrestrial (or “close-range”) photogrammetry. A total of seven campaigns were performed at the landslide foot between 1987 and 1992, covering only a small area of about 100 x 50 m (Fig.2). Stereopairs were taken with a Wild P32 metric camera (Fig.2). Each campaign included 3 photograms that produced 2 photogrammetric models.

The results of each survey were the change in the coordinates of the main points (displacements), the precision ranges between 1 cm in well-defined points (pointing targets for instance) and 10 cm (rock blocks, trees and so on). Maps with contour lines were also produced. The interpretation of this kind of maps is not simple: the variations of the terrain surface are caused by the landslide movement, but also by the soil erosion during rainfalls and the eroding effect of the Vallcebre Torrent at the base of the toe. Although several blocks exhibit displacement of up to 8 m, the variation of the contour lines is very moderate as a whole.

In general, the use of Terrestrial photogrammetry in landslides is not straightforward because of the difficulty of creating a proper set-up with an adequate view over the hill slope. Moreover, specialized and costly equipment has to be available for a precise stereocompilation. Nevertheless, the terrestrial photogrammetry provides information that is continuous over the space, but discontinuous over time.

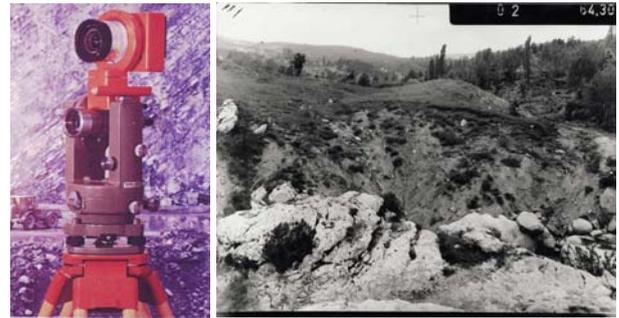


Fig. 2. Left: Wild P32 camera for terrestrial photogrammetry over a theodolite. Right: example of a 6 x 8 cm photogram of Vallcebre landslide toe.

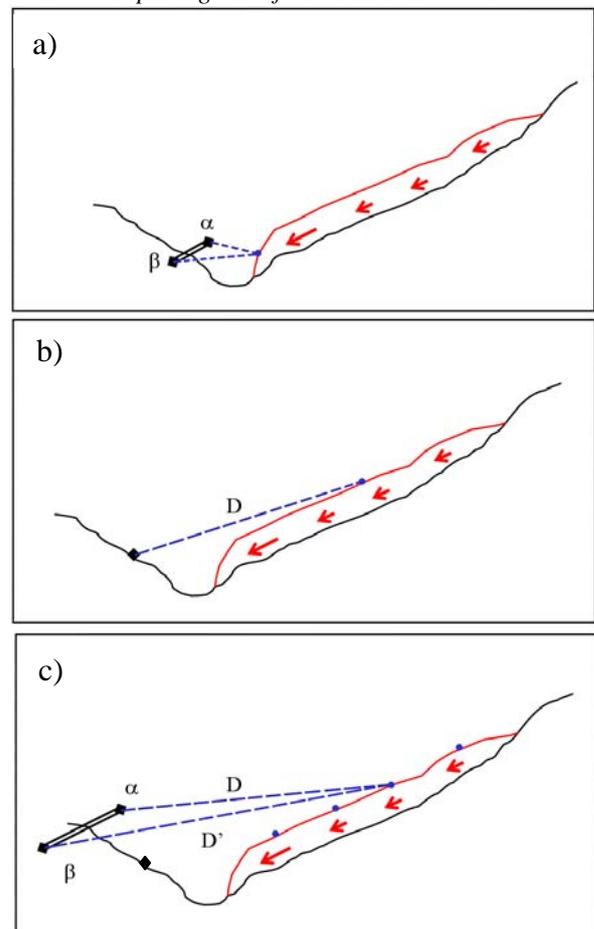


Fig. 3. Triangulation, single distance variation and triangulation schemes.

### B. Triangulation and EDM

From 1987 to 1995, geodetic measurements with theodolite and EDM (Electronic Distance Measurement) were carried out. Between 1987 and 1992, triangulation was undertaken in the same area as the photogrammetry (lower unit, Fig.3a). In the period 1988-1994, three additional points in the middle unit were monitored with single distance variation measurements (Fig.3b). During 1994 and 1995, a “triangulation” (Fig.3c) from new

base points E1 and E2 was extended to 16 points spread out through the whole landslide. The angle measurements were carried out with a Wild T2 theodolite, and the EDM with a Wild DIOR 3002S.

The rate of movement measured during the period 1987-1995 was strongly dependent on the rainfall and the target position within the landslide. Rates up to 4 m per year were observed at certain points near the toe in the rainy years, while almost no displacement occurred during periods of drought. In the middle and upper landslide unit (Fig.1), the rate of displacement was significantly smaller, in the range of 10 to 30 cm/year.

In terms of the precision of the observations, the EDM measurements proved to be more reliable (typically 1cm) than angle measurements with theodolites (around 4 cm at typical distances), at least with the set-up, equipment and sighting distances in use in Vallcebre. This is due to the fact that the precise determination of angles needs greater experience and better environmental conditions (no mist or smog in the line of sight, proper illumination, lack of vibration from strong sunshine), often not completely available in mountain areas at the time when the measurements have to be taken.

### C. The GPS-GNSS surveys

Precisely on this issue of 3D precision, the expected errors for the Global Positioning System might be more balanced in the three axes (1 to 2 cm, depending on the method in use) when compared to theodolite and EDM errors. This point led us to apply GPS techniques to perform systematic monitoring of the Vallcebre landslide. In December 1995, a complete EDM and GPS survey was carried out in order to link the measurements taken with classical methods in the first campaign with the GPS. The equipment used then was a Trimble 4000 SSI model with two dual frequency receivers (Fig.4), and currently we are using two Topcon HiperPro dual constellation receivers.

Most of the old targets were recovered with minor modifications. As new points have been added since 1996, the monitoring network has now around 50 points (Fig.1): most of them are engraved in rock blocks outcropping in the hillside or the top of the casing of the inclinometric boreholes (Fig.4); the radar Corner Reflectors vertex, several steel rods and stakes have been used as well. There are seven additional points on the limestone around the sliding zone. These were the fixed points used to check the GPS accuracy. This network allowed both the measurement of displacements and the comparison with movements obtained with the borehole equipment (inclinometers and wire extensometers) and the Radar measurements.

Although the Fast-Static GPS method (more precise and robust) was partly applied in the first years, the RTK (Real Time Kinematic) is currently in use for productivity reasons. As a result, we can measure the entire network



Fig. 4 Examples of Vallcebre monitoring points with different antenna set-up: telescopic pole (a); tripod with optical plummet over an inclinometer borehole (b).

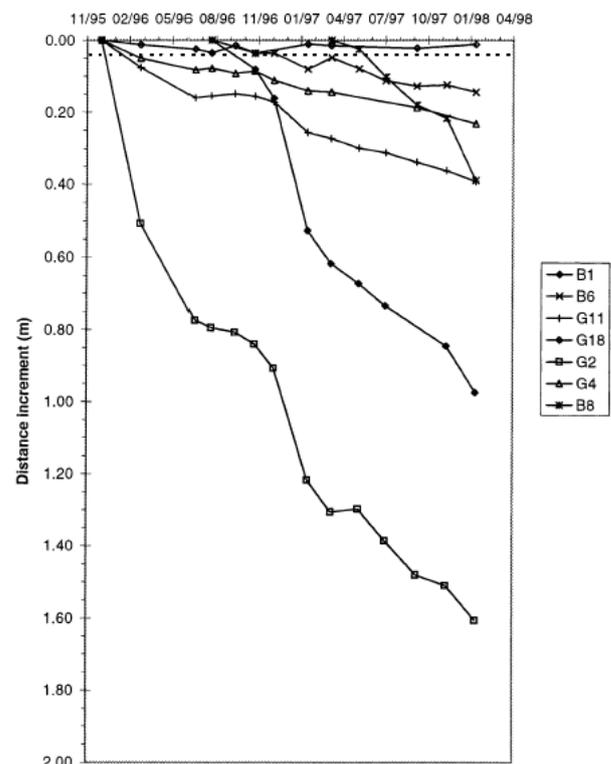


Fig. 5. Example of results of the GPS monitoring: planimetric displacements from the initial position.

within a single day, travelling across the slope by car and on foot.

Fourteen GPS campaigns were carried out from December 1995 to February 1998, one survey every 2 months approximately. Part of the results can be appreciated in Fig. 5. Later on, the campaigns were continued on a yearly basis. More details about the GPS and special considerations for its application to Vallcebre monitoring can be found in [5].

#### D. In-hole (or geotechnical) instrumentation

Between July 1996 and March 1997, 14 boreholes were drilled in the slope (7 in July 1996, the rest in March 1997) and equipped with inclinometers, wire extensometers and open standpipe piezometers. Inclinometers and piezometers were standard devices. As an example, Fig. 6 shows a typical record from one inclinometer, where the slip surface is clearly marked. Measurements were made every 2-3 weeks until the casing deformation prevented the safe and proper sliding of the probe.

On the other hand, the extensometers were wire-type, specially built following a previous design of [8]. They consist of a protected steel wire anchored to the bedrock, below the slip surface, inside a piezometric pipe (Fig.7). After some computation, the wire displacement at the pulley can be related with the horizontal displacement of the landslide. We can quote two major advantages of this device. Firstly, with a potentiometer, it allows the continuous recording of the displacement, particularly necessary to collect information during the concentrated rainfall periods characteristic of the Mediterranean climates (Fig.8). Secondly, the wire extensometer works properly with landslide displacement much larger than the 20-30 cm that would typically break the inclinometric pipe; in fact, in 2012, 16 years after their installation, 3 wire extensometers were still working, with a cumulated total wire displacement of up to 6 meters. Full details of the wire extensometer can be found in [4].

#### E. DInSAR monitoring using corner reflectors

The Space Borne SAR monitoring of landslides has been reported in [9, 10, 11] among others. When applying DInSAR to landslide monitoring, a condition that is difficult to fulfil is that a sufficient number of targets within the area of interest remain coherent during the observation period. One way to overcome this limitation is the deployment of artificial corner reflectors (CRs) that guarantee the obtaining of coherent and high-quality DInSAR estimates. Using CRs, however, demands additional resources; it also prevents historical deformation studies based on archive SAR imagery.

After a detailed discussion of the Vallcebre site suitability for DInSAR with CRs, [6] describe the installation of 7 metallic trihedral CRs (Fig.9) in 2007. The landslide movement is well-oriented (towards the west), and the average slope is only 10°. The deformation rates are moderate enough in order to prevent, in principle, the phase from “rolling over” due to the ambiguous nature of the DInSAR (C-band satellite, with a 35-day revisiting period). One CR was installed directly on the stable rock to be used as reference. The maximum distance between the corners was 300 m to keep the atmospheric bias negligible. The installation was done with utmost care, with the CR symmetry axis oriented towards the satellite orbit.

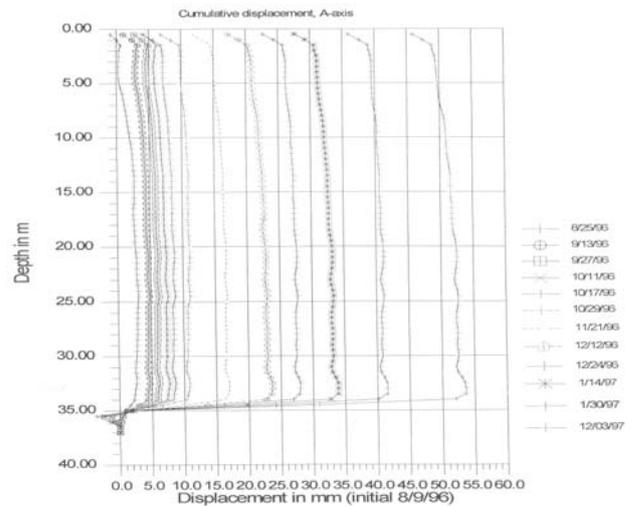


Fig. 6. Horizontal displacement profile obtained from inclinometer S7.

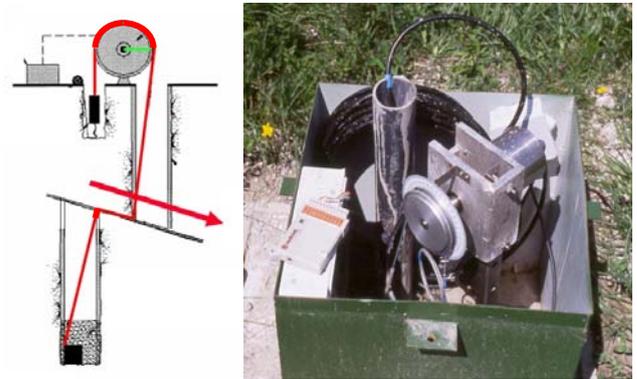


Fig. 7. A sketch of the borehole wire extensometer. The picture corresponds to the extensometer head. The cable for the piezometer (black) can also be appreciated.

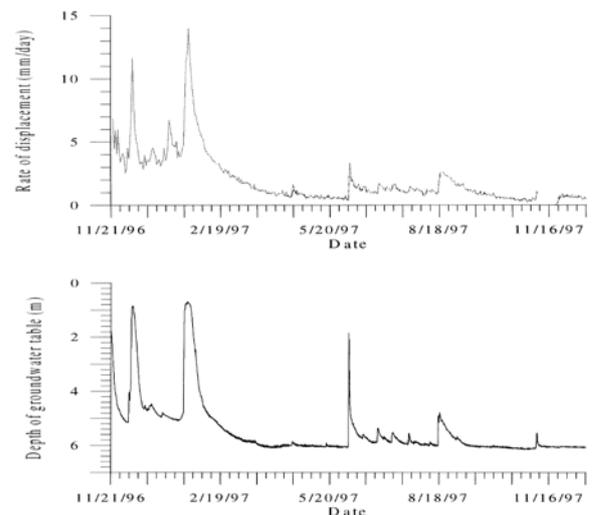


Fig. 8. Measurements at borehole S2. Above: rate of wire displacement. Below: groundwater table fluctuation measured by the piezometer. A perfect synchronism between rate and water level can be appreciated.



Fig. 9. Corner Reflectors (CRs) manufactured by NPA used to monitor the Vallcebre landslide. Examples of installation on a rock block or directly over the terrain.

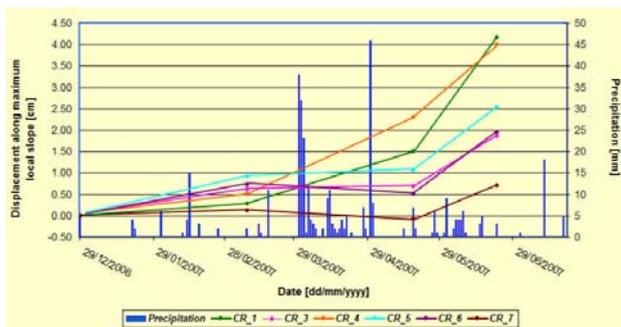


Fig. 10. Temporal evolution of the displacements of the CRs projected in the direction of the maximum local slope angle. Precipitation is also presented

Figure 10 displays an example of the results derived from the DInSAR monitoring using four descending Envisat SAR images. It can be observed that the displacements were small between the end of December 2006 and the beginning of March 2007, while for CR1 and CR4 there is a substantial increase in displacements in March and April associated with abundant rainfall.

#### F. Non-interferometric GBSAR monitoring

[12, 13] presented the application of the Ground-Based SAR (GBSAR) to landslides. In 2010-2011, the lower part of the Vallcebre landslide was monitored using a GBSAR. In this case, we did not use interferometry based on the phase but a new procedure to process the amplitude component of the GBSAR data acquired in discontinuous mode. This methodology intends to overcome several well-known drawbacks of the radar interferometry, especially in a landslide environment: loss of coherence; lapse of time between acquisitions; aliasing effect; atmosphere influence, etc. The use of geometric features of the amplitude images combined with a matching technique is fully described in [7].

Between February 2010 and September 2011, this technique was applied to the lower unit of the Vallcebre landslide in order to evaluate the performance of the non-interferometric GB-SAR approach. In this period, eight measurement campaigns were carried out using the IBIS-L Ku-band GB-SAR (IDS SpA, Fig. 11). In each campaign, 15 small CRs were deployed in and around the target area (11 inside, 4 outside as reference).



Fig. 11. Picture of the IDS GBSAR system. The synthetic aperture is obtained through the movement of the radar sensor (yellow box) along the rail.

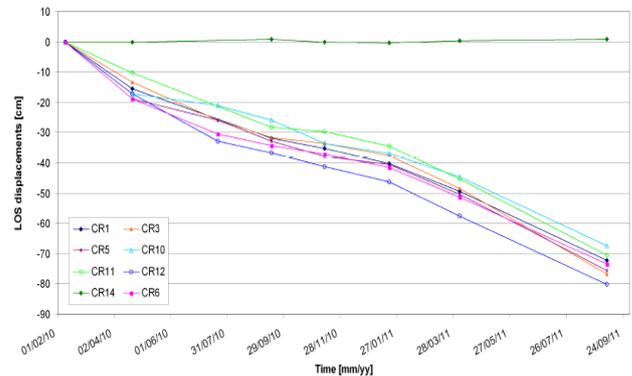


Fig. 12. Measured displacements with non-interferometric GBSAR between February 2010 and September 2011 at eight small CRs.

In parallel to the GBSAR measurements, five surveying campaigns were carried out to validate the results obtained with the GBSAR. The analysis of the total measurements obtained during the 19 months permitted the validation of the technique. Displacements up to 80 cm were measured in the lower part of the lower unit (Fig.12).

### III. PRECISION CONSIDERATIONS AND SYSTEM CROSS-CHECKS

As the different systems were applied to certain common points, the resulting displacements can be compared, and practical precisions, advantages and drawbacks may be derived.

For the superficial methods, it can be concluded that the GPS measurements show better trends and stability than the Total Station measurements, at least with the Vallcebre conditions and equipment. An example is given in Fig. 13. Moreover, the GPS surveying is “all-weather” in practice, an additional advantage when working in mountainous areas.

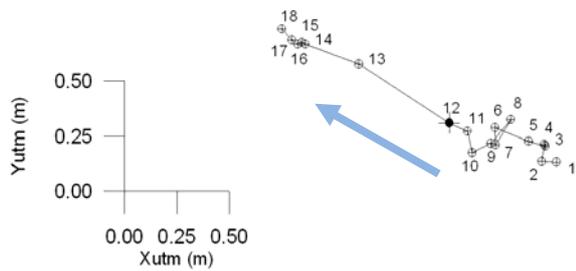


Fig. 13. Apparent change in the behaviour of point G2 when monitored with classical surveying (dots 1 to 12) or with GPS. Blue arrow points towards surveying station.

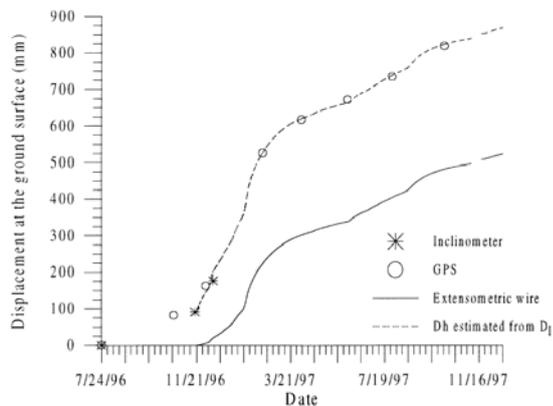


Fig. 14. Comparison of the wire extensometer displacements against the GPS and the inclinometric measurements of the Vallcebre borehole S2: solid line, total wire readings, D1; dashed line, corrected horizontal component of wire displacement, Dh.

A theoretical composition of errors, along with independent checks of the GPS results obtained at fixed stable points, let us establish the following errors (in terms of standard deviation) for the GPS monitoring with the RTK method in Vallcebre (currently still in use): 16 mm in the horizontal plane and 24 mm in elevation.

The GPS measurements have also been used to check inclinometer and wire extensometer displacements at several boreholes [4]. As an example, in Fig. 14 a cross-check is presented. In Vallcebre, the inclinometric readings were possible only until 200 mm of total displacement for the top of the boreholes due to the casing deformation in the failure zone. The wire extensometers and GPS measurements have been continued without trouble beyond these figures.

Compared with the standard GPS (campaign by campaign), the extensometric technique has the advantage of being an automatic and continuous measuring system which can be correlated with rainfall and piezometric heads. On the other hand, the GPS yields the direction of the movement and the  $\Delta Z$  as well as  $\Delta$ Distance. It is worth noting that the GPS can also be installed and operated in continuous ([14] for instance).

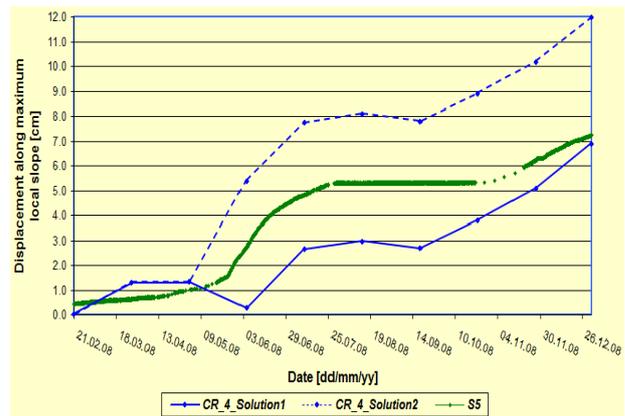


Fig. 15. Displacement time series estimated with DInSAR over the CR4 Corner Reflector, and measured by the wire-extensometer S5, located at a distance of 84m.

The cross-checking has also been useful for the radar measurements, validating or improving the remote sensing techniques. For instance, in Fig. 15 a phase unwrapping problem is recovered.

Figure 15 shows two displacement time series of CR4. The continuous blue line represents one phase unwrapping solution, which has an accumulated displacement of 6.9 cm and which shows an upward displacement of 1.1 cm between April and June 2008. Considering the kinematics of the landslide, this type of movement can be considered very unlikely. For this reason, a second solution was chosen, depicted with a dashed line and which shows an accumulated displacement of 11.9 cm in 11 months. The same figure shows the displacement measured by the wire extensometer S5, which is located relatively close to CR4. It is interesting to compare the time series of CR4 (dashed line) and S5. They display quite a similar temporal evolution, which includes a strong deformation gradient between June and July, followed by a stationary period until September and a second, less strong deformation gradient. This similarity confirms the one phase shift applied to the CR4 curve. The curves do not overlap due to the fact that one point is 84 m from the other.

The GBSAR amplitude technique presented in #2.F has also been validated against the continuous monitoring that is given by the wire extensometer system. Prior to performing a proper comparison, the CR5 and CR7 Line-Of-Sight (LOS) results (Fig.12) have been projected onto the total displacement vector (estimated from GPS measurements in the area). The method can be found in [7]. Now, the CR5 and CR7 GBSAR displacements can be compared with the closer wire extensometer (S11 and S2 respectively, Fig. 16). Dashed lines show straight lines with a slope of 1 : 1, i.e., the perfect fit, which is almost reached.

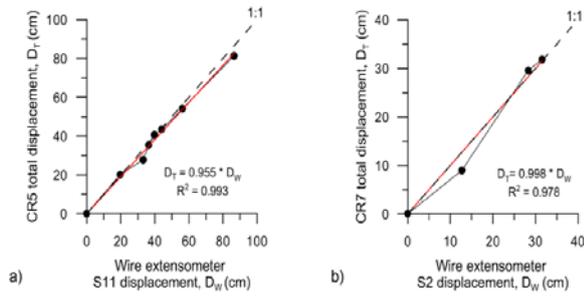


Fig. 16. Charts showing GBSAR total displacement against wire extensometer displacement: (a) for CR5 and S11, and (b) for CR7 and S2.

#### IV. SUMMARY AND CONCLUSION

A general overview of the methods used in Vallcebre for measuring the displacements of the landslide has been given. More details of the systems presented here in abstract, along with the full formulation, validation and conclusions can be found in [1, 6, and 7]. A summary of the main characteristics of them is given in Table 1. This table is in accordance with [2, 5], but the values are valid only for the specific constraints and equipment in Vallcebre. The characteristics of the methods are summarized along with the precision and main results achieved. The *complexity* column aims to quantify the refinement of the equipment and personnel involved, and the *cost* column includes the amount of the material and work needed to obtain the data.

The methods in the table should not be considered as excluding alternatives but as complementary systems to be applied progressively or in different areas, as has been explained in section 2. For example, the photogrammetry was used in the toe of the slide to monitor a fairly small but very active area. The EDM & triangulation (and later the GPS) were implemented to cover the whole hillside and capture mean movements as big as 1 meter per year with minimum investment.

The surveying with EDM and GPS were carried out with a given frequency (i.e. campaigns each two months or each year), so the results are discontinuous over time. Although not implemented in Vallcebre, it is technically possible to automate the procedure for the continuous monitoring of the displacements (robotic total station, permanent GPS stations).

The installation of in-hole devices was possible only when additional funding had been obtained in order to drill the boreholes and instrument them. The inclinometers and the wire extensometers complement each other very well. The former had a short 'life' as the landslide was fairly active, but they produced high-quality information on landslide displacement profiles, velocities and the position of the shear surface immediately after their installation. In contrast, at the

early stages of deformation, the wire extensometers may only record negative displacements that are not simply related to the superficial ones. However, once the inclinometers were lost, the wire extensometers have allowed continuous recording, even for very large displacements. Since 1996, when they were first installed, the wire extensometers have provided a measurement readout each 20 minutes and, at some points, the cumulative displacement has been as high as 6 m. The accelerations in the rate of displacement can be easily related to rainfall and groundwater rises (Fig.8), especially during critical rainy events, when other systems are not in operation. Most of the piezometers and 3 wire extensometers installed in Vallcebre were still operational in 2012. Around 2010 an automatic meteorological station was installed in the centre of the landslide in order to get the significant precipitation, because the rainfall may vary suddenly from one point to another.

On the other hand, the GPS results helped to calibrate the parameters of the wire extensometer equation [4], they allowed a convenient check of the displacements, and they permitted the extension of the measurements to more points in the landslide in addition to the boreholes.

As demonstrated in the previous sections, all the results are in fairly good accordance when adequate corrections and error considerations are done. The redundancy between methods is very advisable so as to detect malfunctions of the devices or cover gaps in data.

With the years, some improvements in the electrical power (solar panels) and in the data transmission have been introduced in the Vallcebre set-up. Currently, the wire extensometer and the piezometer readings can be downloaded from a remote location by means of the mobile phone network in order to get the monitoring of the landslide in real time in the headquarters.

Nowadays, the aforementioned 'Vallcebre real-scale laboratory' is ready and waiting to receive new monitoring systems for assessing their performance!

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Table 1. Overview of the methods used in Vallcebre landslide monitoring

	Method	Results	Typical range in Vallcebre	Typical precision in Vallcebre	Complexity	Cost	Comments
Surface	Terrestrial Photogrammetry	Maps (points with $\Delta X, \Delta Y, \Delta Z$ , contour lines)	30 to 45 m	10 mm for well-defined points	Medium	High	High precision equipment and skill is needed
	EDM& Theodolite	$\Delta$ dist. or $\Delta X, \Delta Y, \Delta Z$	15 to 1500 m	7 mm for $\Delta$ dist, >25 mm for the rest	Medium	Low	Practical experience in surveying is needed
	GPS	$\Delta X, \Delta Y, \Delta Z$	800 to 2300 m	12-16 mm (horiz.) 18-24 mm (elev.)	Low	Low	Discontinuous over time
	CR based DInSAR	Displacement L.O.S.	n/a	a few mm	High	High	Each 35 days with Envisat
	Non-interferometric GBSAR	Displacement L.O.S.	500-800m	below 1 cm	High	High	Often, CRs must be installed each campaign
In-hole	Inclinometer	$\Delta X, \Delta Y$	15 to 45 m depth	1 to 2 mm	Low	Medium	Discontinuous over time
	Wire extensometer	$\Delta D_{wire} \rightarrow \Delta D_{horiz}, \Delta D_{vert}$	15 to 45 m depth	0.5 mm in the wire length <sup>1</sup> .	Low	Medium	Continuous log, discontinuous/continuous download
	Piezometer	$\Delta P_w \sim \Delta H_w$	15 to 45 m depth	30mm water head	Low	Low-Medium	Continuous log, discontinuous/continuous download

1: After a good calibration of the wire equation, 2 mm in the corrected surface displacement can be achieved

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