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Past, Present and Future Monitoring at the Vallcebre Landslide (Eastern Pyrenees, Spain)

Josep A. Gili [1,*], Jose Moya [1], Jordi Corominas [1], Michele Crosetto [2] and Oriol Monserrat [2]

1 Department of Civil and Environmental Engineering, Division of Geotechnical Engineering & Geosciences, Technical University Catalonia (UPC-BarcelonaTech), 08034 Barcelona, Spain; jose.moya@upc.edu (J.M.); jordi.corominas@upc.edu (J.C.)
2 Remote Sensing Department, Geomatics Division, Centre Tecnològic Telecomunicacions Catalunya (CTTC/CERCA), Castelldefels, 08860 Barcelona, Spain; michele.crosetto@cttc.es (M.C.); oriol.monserrat@cttc.es (O.M.)
* Correspondence: j.gili@upc.edu

Featured Application: Monitoring of very slow landslides with Classical and Novel Techniques.

Abstract: Works carried out to monitor the displacements of the Vallcebre landslide (Pyrenees range, NE of Spain) since 1987 are presented. The landslide, which extends over an area of about 0.8 km^2 and affects more than 20×10^6 m^3, has experienced displacements of up to one meter per year in some points and periods. It has been periodically monitored since 1987, using a wide range of surface and in-hole techniques: triangulation with theodolite, Terrestrial Photogrammetry, Electronic Distance Measurement, GNSS-GPS, inclinometers, wire extensometers, piezometers, DInSAR (satellite) and GBSAR (terrestrial). The results obtained using new techniques are compared with those obtained with GNSS-GPS and a 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 systems play potentially valuable roles in providing meaningful data for monitoring at different study stages. In the near future, we envisage the installation of a Distributed Fiber Optic array to monitor the risk with a certain space and time continuity. After the evaluation of the precision and advantages of the different methods, the complementary use of some of them is strongly recommended.

Keywords: monitoring; landslides; photogrammetry; global positioning system; in-hole wire extensometer; DInSAR; GBSAR

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1. Introduction and Site Description

The Vallcebre landslide is located in the Eastern Pyrenees, approximately 125 km north of Barcelona, Spain (Figure 1). Its situation, geological context and a complete geomorphological description can be found in [1,2]. The present paper is an expanded and updated version of a previous work [3] where we described the landslide as a translational slide with a stair-shape profile. As in most landslides, its structure and behavior are not simple. The landslide is 1200 m long and 600 m wide, involving an area of 0.8 km^2, which shows superficial cracking and distinct ground displacements (Figure 2). The mobilized material consists of a set of shale, gypsum and claystone layers gliding over a thick limestone bed. A geological cross-section is presented later in Section 2.4. The landslide consists of three main slide units, which show a decreasing thickness towards the landslide toe. Each unit is formed by a gentle slope surface bounded in its uphill edge by a scarp of a few tens of meters high. At the base of each scarp, an extension area develops in the form of a crack system and a graben [1]. This fact indicates that the lower units move more rapidly than upper ones, which has been repeatedly confirmed by an installed monitoring network [1,2].

Figure 1. Location of Vallcebre valley (red arrow) within the Pyrenees range, NE of Spain.

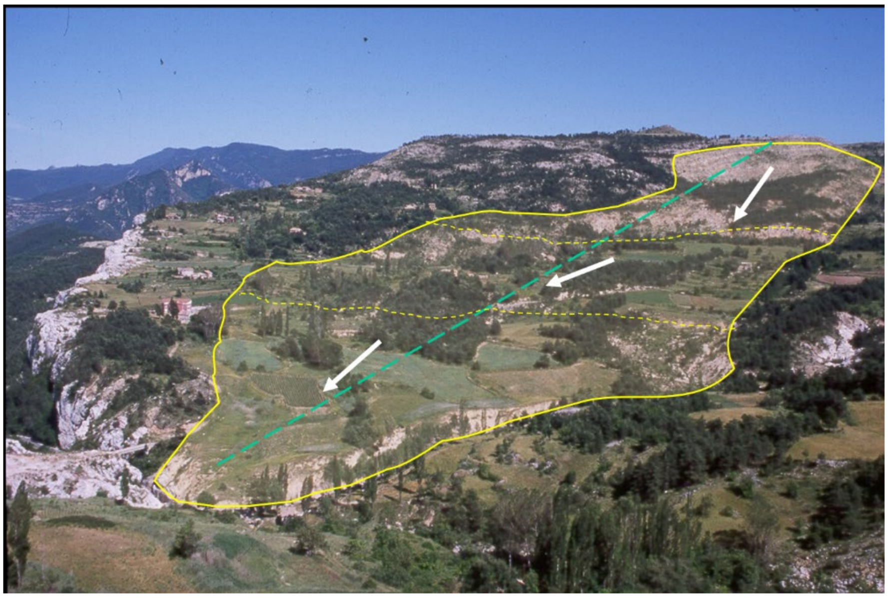

Figure 2. General view of the Vallcebre landslide from W. The unstable area (yellow contour) is about 0.8 km^2, has an average slope of only 17° (green line), and is sliding as a translational slide. The white arrows are the average slide directions of the upper, middle and lower units, which are separated by scarp zones (dashed yellow lines).

The average slopes of both the topography and the basal shear surface in the middle and lower unit are gentle, i.e., in the range between 6 and 10°. The basal shear surface depth is 42 m in the middle unit and 15 m in the lower one, being quite planar for most of the sliding surface.

Complete information on the geology and geotechnics of Vallcebre, and a stability analysis, are beyond the scope of this article, but can be found in [1–8].

Figure 3 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. Consequently, most of the monitored points were located there.

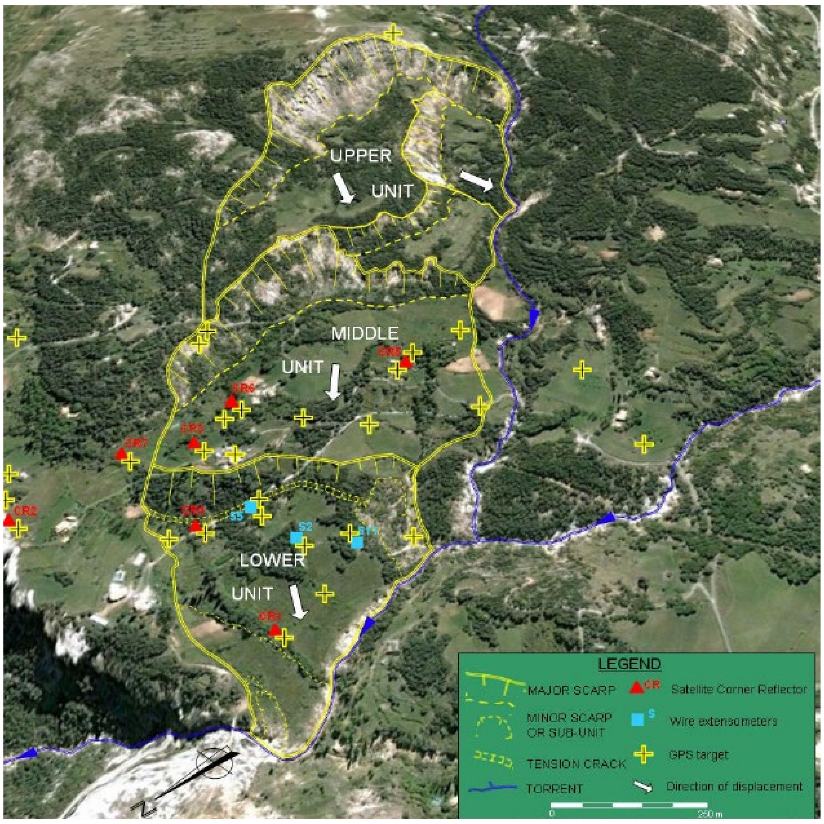

Figure 3. Geomorphological scheme of the Vallcebre landslide superimposed over a vertical aerial image. Several GPS benchmarks, corner reflectors and borehole extensometers have been highlighted with symbols.

The measurement of displacements is very often the simplest way to observe the evolution of a landslide and to analyze 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., [9,10]). This second work, also known as the 'Red Book' of Geotechnical Instrumentation and Monitoring, is due to John Dunnicliff. Several of these methods have been used in Vallcebre since 1987, beginning with "classical" surveying and photogrammetry, and using Global Positioning Systems (GPS/GNSS) from 1995. In 1996, this site was included in the framework 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 (Figure 3).

In 2004–2005, multipoint piezometers were installed in three additional boreholes. Later, the Vallcebre landslide was included in an 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, 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. For instance, Laser Scanning (both Terrestrial or Aerial) have been disregarded because the ground displacements, mainly parallel to the topography, would be difficult to detect; also the vegetation would mask the results.

In the paper, Section 2 describes the measuring systems. 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 tested in Vallcebre. The aforementioned comparison was made in terms of cost, ease of use, precision and continuity of the results.

2. Monitoring Methods Used in Vallcebre and Sample Results

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

2.1. 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 × 50 m (Figure 4). Stereopairs were taken with a Wild P32 metric camera (Figure 4). Each campaign included three photograms that produced two photogrammetric models.

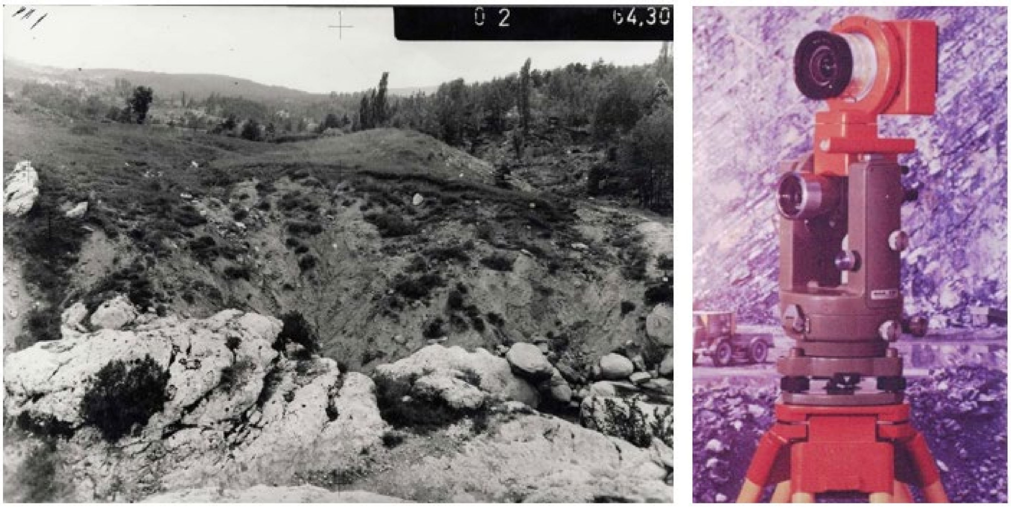

Figure 4. **Left**: example of a 6 × 8 cm glass plate photogram of landslide toe taken from the Vallcebre Torrent. **Right**: Wild P32 camera for terrestrial photogrammetry over a theodolite, which was used for the landslide toe monitoring between 1987 and 1992.

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 (Figure 5). 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 (Figure 5).

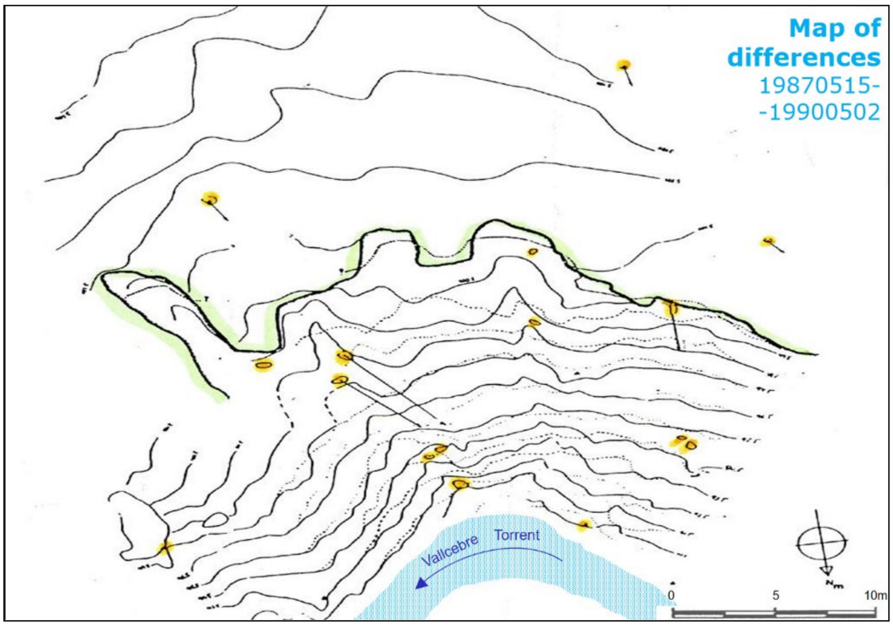

Figure 5. Terrestrial photogrammetry sample result: Map of differences between two campaigns (one-meter contour-line interval) at the landslide toe (Figure 4).

At that time, the use of terrestrial photogrammetry in landslides was not straightforward, because of the difficulty of creating a proper setup with an adequate view over the hill slope. Moreover, specialized and costly equipment had to be available for a precise stereocompilation. Although out of the scope of this paper, it is worth to say that the photogrammetry processing has evolved in the last decade towards automation, ease of use and low cost, thanks to the so-called Structure from Motion (SfM) concept [11–13]. In parallel, the use of drones (or UAS) as aerial photogrammetry platforms permits to overcome the point-of-view issues during acquisition [12–17] In this way, photogrammetry is once again a powerful landslide monitoring technique, providing information that is almost continuous in space, but discontinuous in time.

2.2. Triangulation and Electronic Distance Measurement

From 1987 to 1995, geodetic measurements with theodolite and EDM (Electronic Distance Measurement) were carried out. Between 1987 and 1992, up to 17 points were triangulated in the toe of the lower unit, mainly for orientation of the photogrammetric models (Figure 6a). In the period 1988–1994, three additional points in the middle unit were monitored with single distance variation measurements (Figure 6b). During 1994 and 1995, a "triangulateration" from new base benchmarks E1 and E2 (Figure 6c) was extended to 16 points spread out through the whole landslide. The angle measurements were carried out with a Wild T2 theodolite (Wild, Heerbrugg, Switzerland, 1975), and the EDM with a Wild DIOR 3002S (Wild, Heerbrugg, Switzerland, 1988).

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 (Figure 7). In the middle landslide unit (Figure 3), the rate of displacement was significantly smaller, in the range of 1 to 30 cm/year.

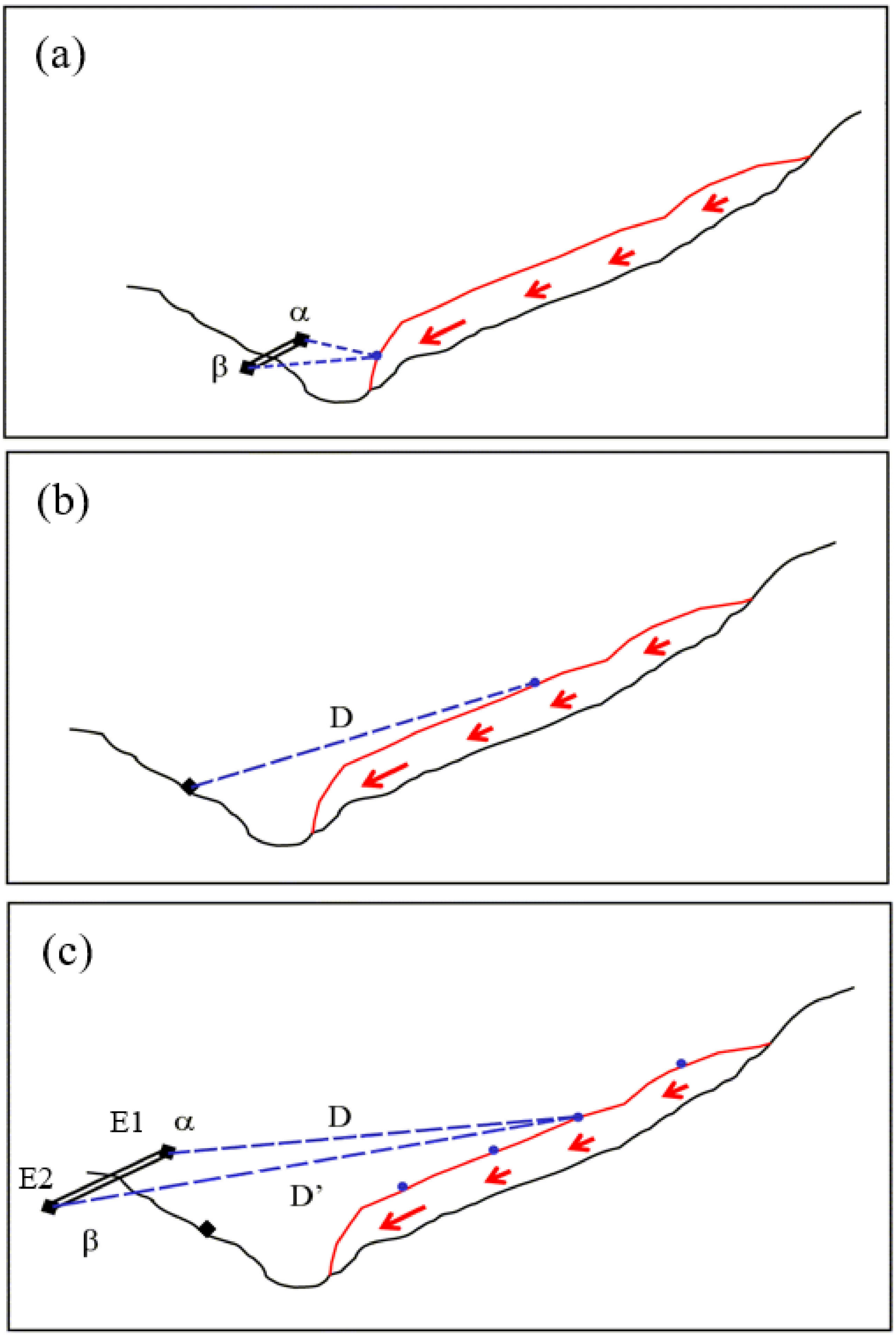

Figure 6. Schemes for the triangulation (**a**), single distance variation (**b**) and triangulateration (**c**) methods as used in the Vallcebre landslide from 1987 to 1995.

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

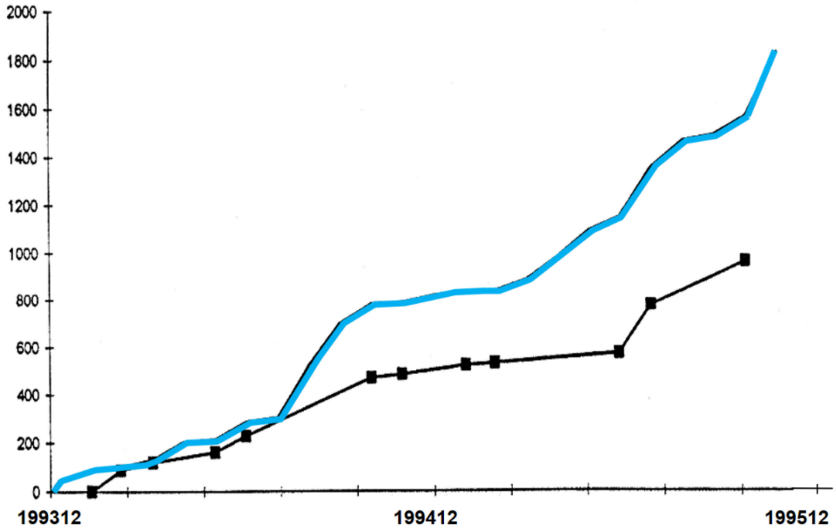

Figure 7. First tentative correlation between the displacement of a point in the lower unit (mm, black line) and the cumulative rainfall (mm, blue line), during 1994–1995.

2.3. The GPS-GNSS Surveys

Following the discussion on the precision of the observations, the expected errors for the Global Positioning System (1 to 2 cm, depending on the method in use [5]) were lower when compared to theodolite and EDM errors. Additionally, the GPS precision was more balanced in the three axes [5]. These facts led us to apply GPS techniques to perform systematic monitoring of the Vallcebre landslide. In December 1995, a complete double survey (EDM and GPS) was carried out in order to link the measurements taken with classical methods with the first GPS campaign. The equipment used then was a Trimble 4000 SSi model with two dual frequency receivers (Trimble, Sunnyvale, CA, USA, 1995, Figure 8). Currently, we are using two Topcon HiperPro dual constellation receivers (Topcon Positioning Systems, Livermore, CA, USA, 2005).

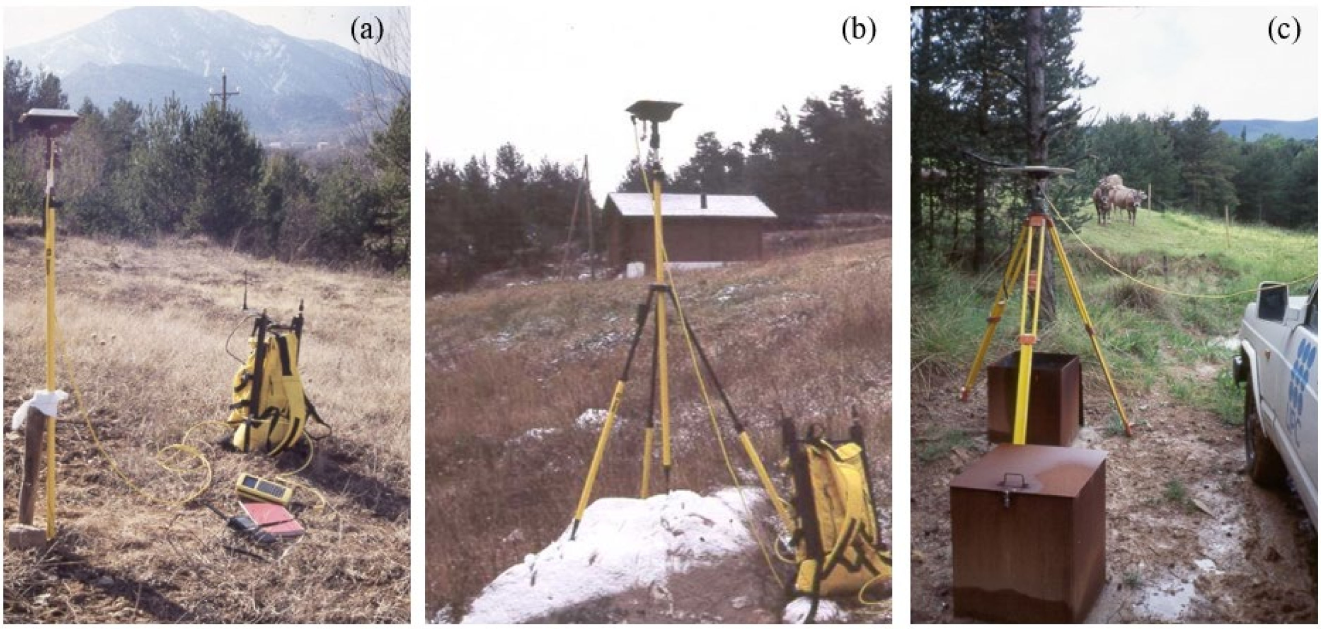

Figure 8. Examples of Vallcebre monitoring points with different antenna setup: telescopic pole (**a**); pole with mini-tripod (**b**); ground-plane antenna over a tripod, centered with an optical plummet over an inclinometer borehole (**c**).

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 (Figure 3), consisting on engravings in rock blocks outcropping in the hillside, steel rods, stakes, and the top of the casing of the inclinometric boreholes (Figure 8); the radar Corner Reflectors vertexes were incorporated to the GPS network as of 2006. 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, RTK (Real Time Kinematic) is currently in use for productivity reasons [5]. Currently, we can measure the entire network 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 (Figure 9a). Later on, the campaigns were continued on a yearly basis (Figure 9b), 36 GPS surveys until now. Average displacement rates derived from GPS campaigns show a sustained regime of velocities: the annual displacement depends on the precipitation of the year (total value and peak periods). More details about the GPS and special considerations for its application to landslide monitoring can be found in [5,18,19].

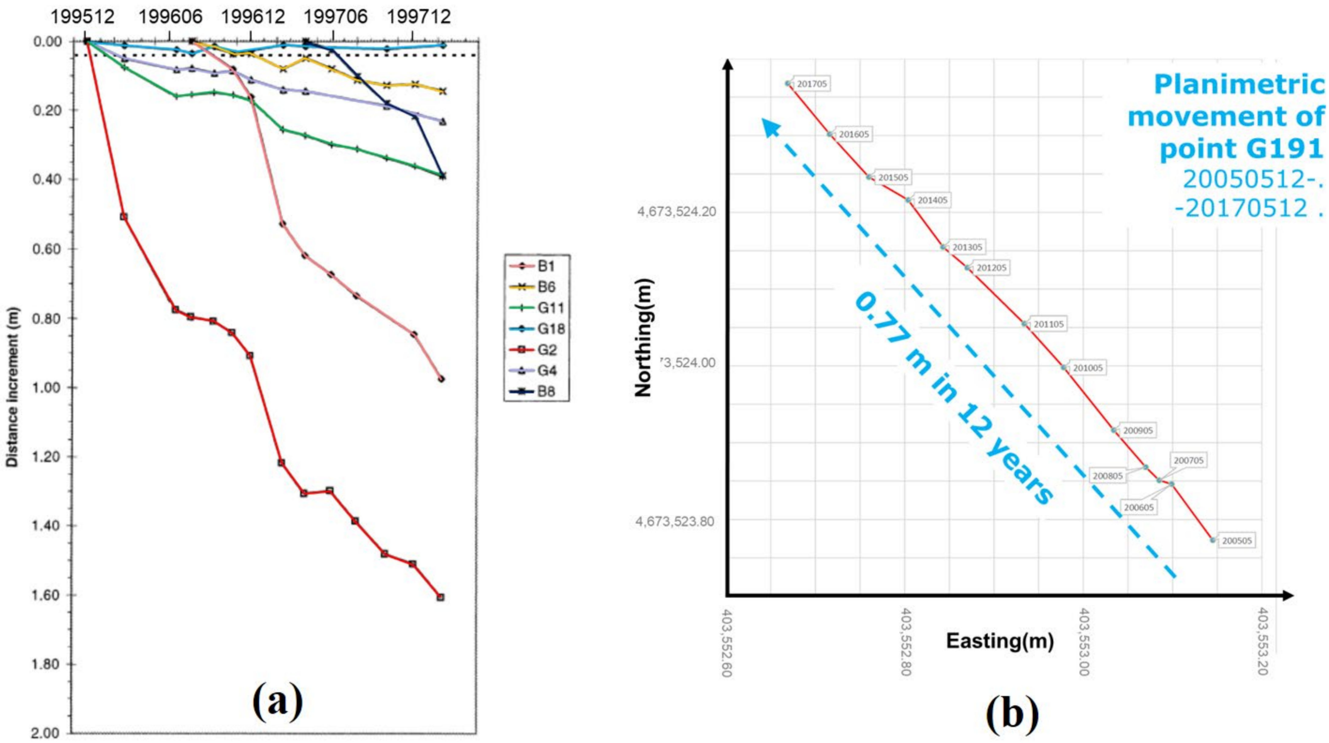

Figure 9. Examples of results of the GPS monitoring (**a**) planimetric displacements from the initial position in the period 1995–1998 (**b**) planimetric movement of one point during the yearly campaigns.

2.4. In-Hole (or Geotechnical) Instrumentation

Between July 1996 and March 1997, 14 boreholes were drilled in the slope for reconnaissance; 3 more were drilled in 2005 (Figure 10). Some of them were equipped with inclinometers, wire extensometers and open standpipe piezometers. Inclinometers and piezometers were standard devices. As an example, Figure 11 shows one inclinometer head and its typical record, 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.

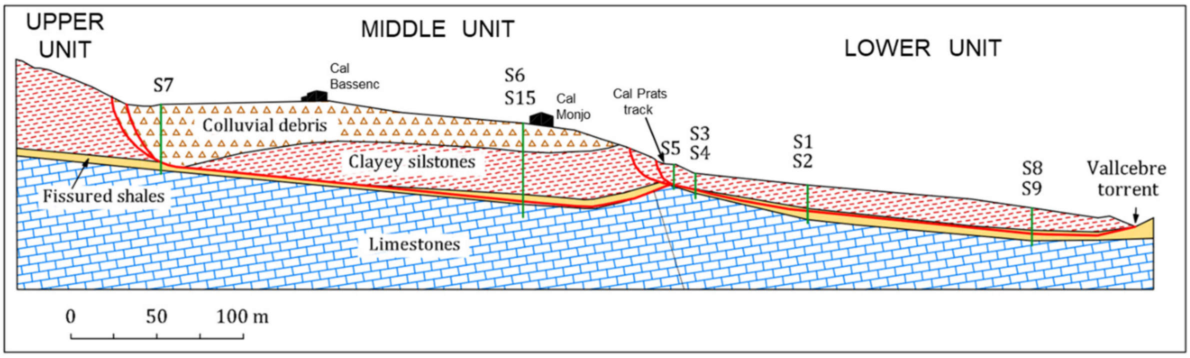

Figure 10. NE-SW geological cross-section of the Vallcebre landslide according to [1,2]. Some of the 17 boreholes drilled are shown, which were equipped with inclinometers, wire extensometers (for shear displacement) and vibrating wire piezometers.

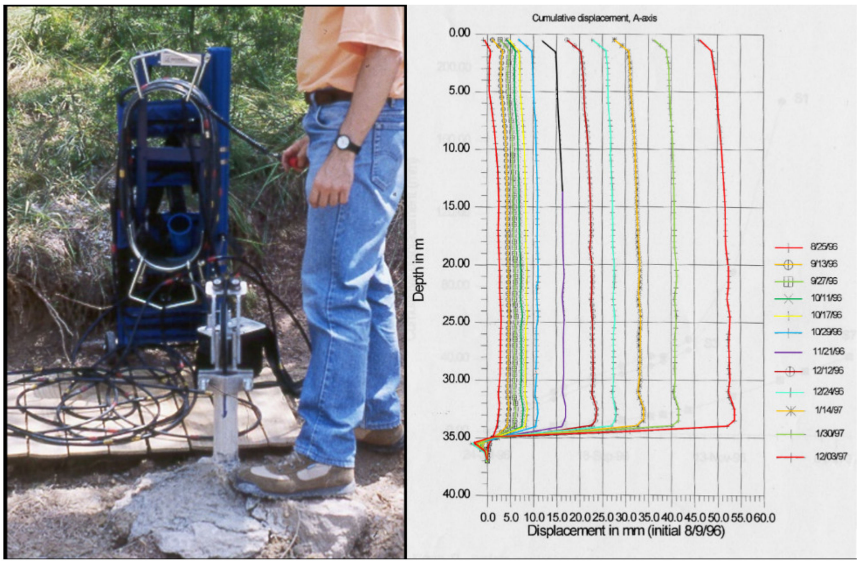

Figure 11. Left: view of the head of a borehole during the measurement with the inclinometer. **Right**: graph with the successive displacement profiles from August 1996 to December 1997. The main slip surface appeared to be 34 m deep. The pretty constant deformation profile corresponds with a translational slide.

On the other hand, the extensometers were wire-type, specially built following a design described in [20]. They consist of a protected steel wire anchored to the bedrock, below the slip surface, inside a piezometric pipe (Figure 12). After some computation, the wire displacement at the pulley can be related with the horizontal displacement of the landslide (Figure 13). 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 (Figure 14). Secondly, the wire extensometer works properly with big landslide displacements, 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 m. Full details of the wire extensometer can be found in [4].

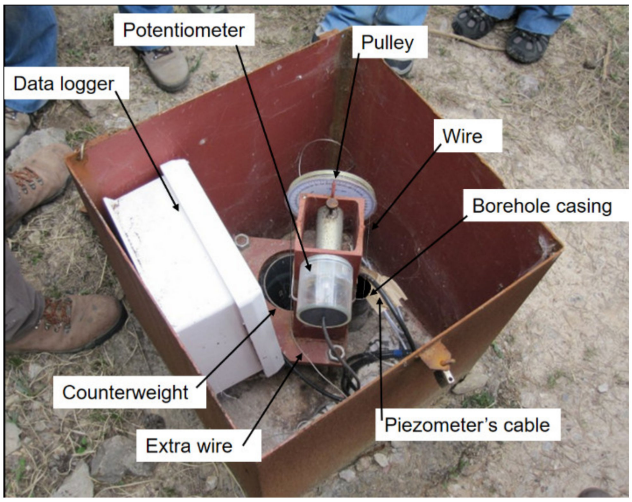

Figure 12. Head of one of the borehole wire extensometers installed at Vallcebre. The cable for the piezometer (black) can also be appreciated.

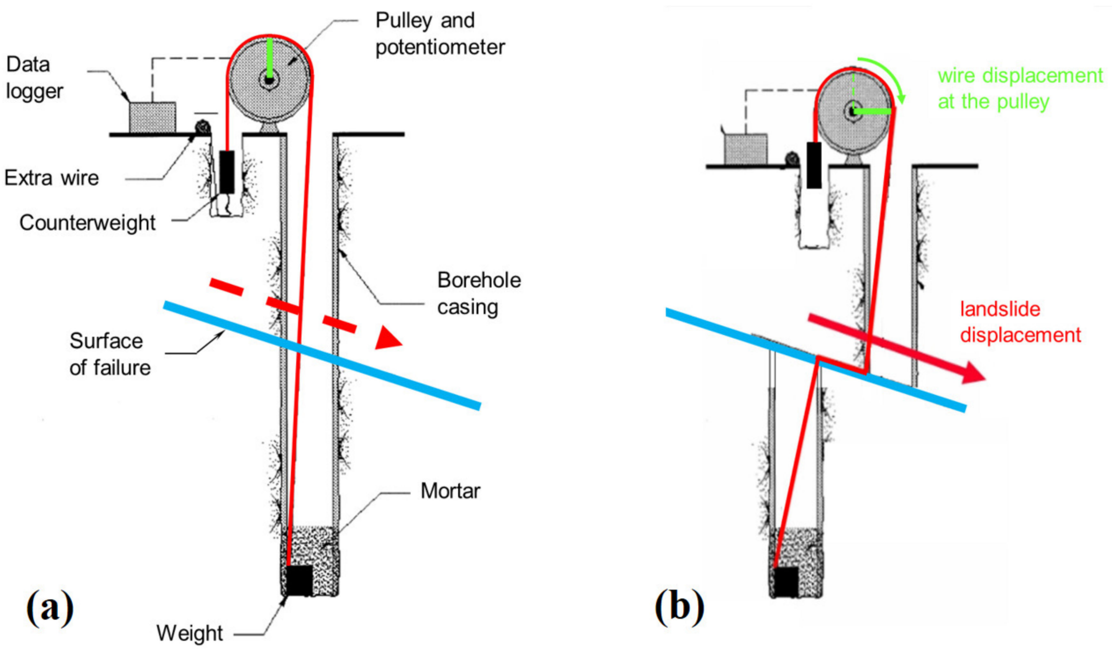

Figure 13. Sketch of the borehole wire extensometer. (**a**) just after installation; (**b**) after some shear displacement of the landslide (idealized). The relationship between the wire displacement at the pulley and the horizontal displacement of the landslide depends on the width of the shear zone and the borehole diameter [4]. The smaller the borehole diameter, the faster the wire response.

2.5. DInSAR Monitoring Using Corner Reflectors

The Space Borne SAR monitoring of landslides has been reported in [21–23] and elsewhere. When applying DInSAR to landslide monitoring in forested areas, 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 ensure coherent, 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, in 2006, of 7 metallic trihedral CRs (Figure 15) to be observed with the ENVISAT (C-band, with a 35-day revisiting period). The Vallcebre landslide movement is favorably oriented (towards the west) and has a gentle slope. Additionally, the deformation rates are moderate enough in order to prevent, the phase from "rolling over" (problem due to the ambiguous nature of the DInSAR). One corner (CR_2) 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 radar line of sight [6].

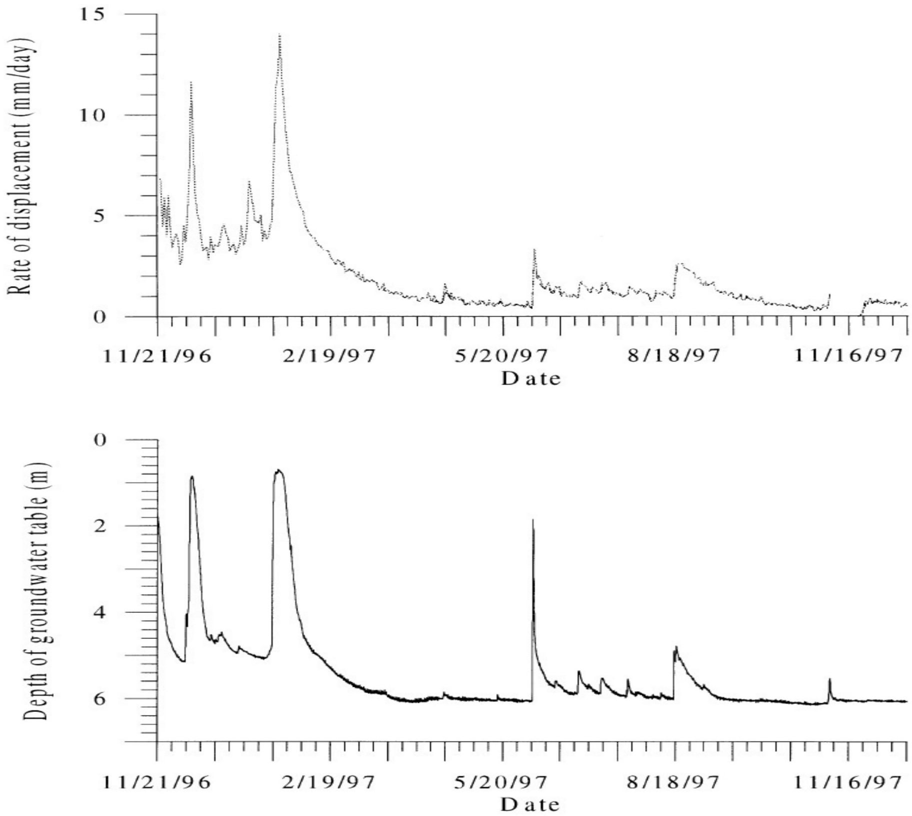

Figure 14. Measurements at borehole S2. Above: rate of displacement derived from the wire extensometer. Below: groundwater table fluctuation measured by the piezometer. A perfect synchronism between rate and water level can be appreciated. This correlation means that groundwater has a big influence in the balance of forces controlling the landslide dynamics.

Figure 15. Corner Reflectors (CRs) used for DInSAR monitoring at the Vallcebre landslide [6]. Examples of installation on a big rock block (**left**) or directly over the terrain (**right**).

In Figure 16a, the CRs are clearly distinguishable in an amplitude image of the landslide. Processing interferometrically four 2007 descending ENVISAT images, the map of the rate of movements was obtained (Figure 16b). As an example, Figure 17 displays the resulting displacements, which were small between the end of December 2006 and the beginning of March 2007, whereas for CR1 and CR4 there is a substantial increase in March and April associated with an abundant rainfall period.

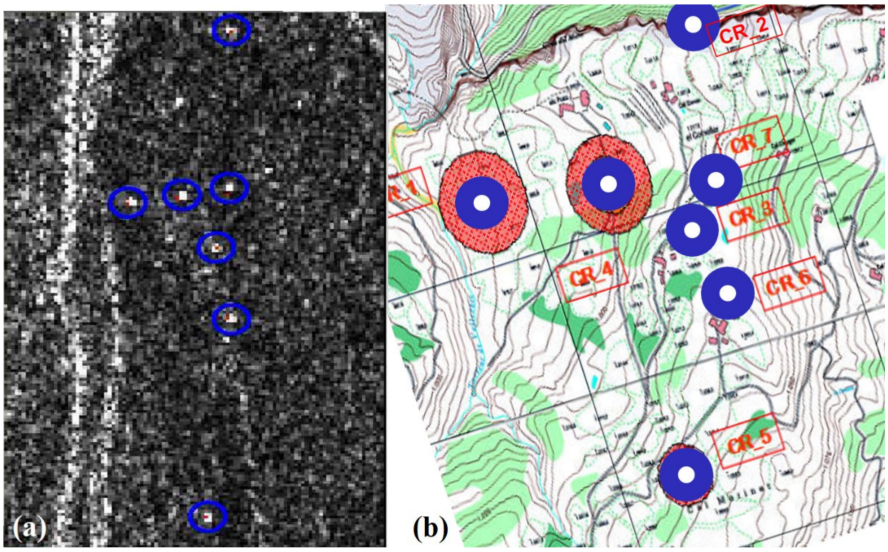

Figure 16. (**a**) the 7 Corner Reflectors appear as bright spots in a 2007 radar amplitude image; (**b**) the concentric circles on the map represent the rate of movement of the CRs during the first half of 2007.

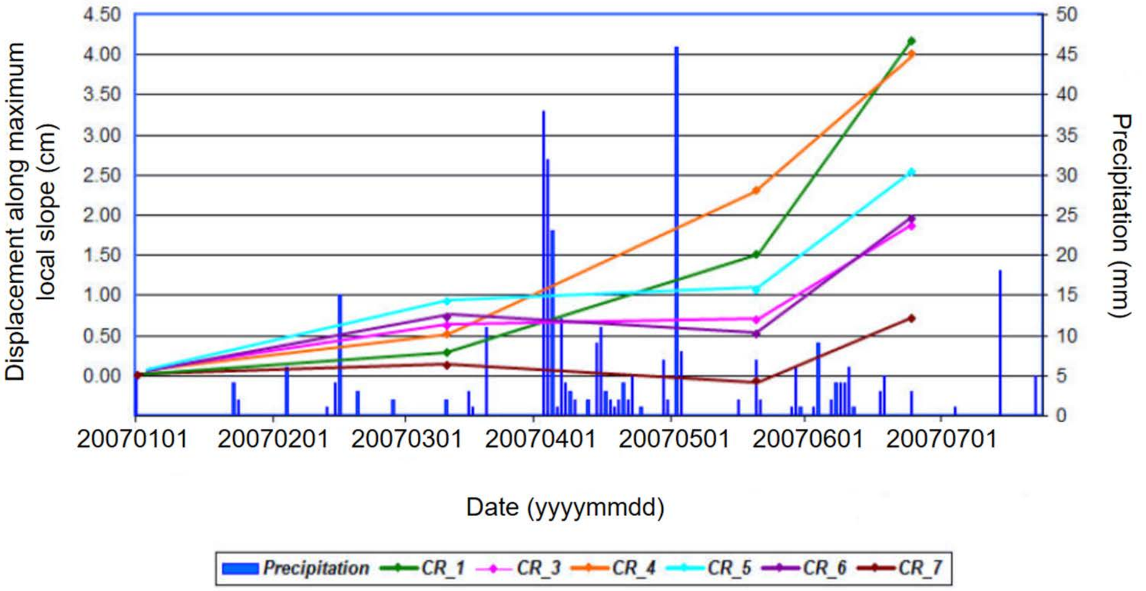

Figure 17. Evolution of the displacements (cm) of the CRs during the first half of 2007. The relative Line-Of-Sight (L.O.S.) displacement was corrected to the direction of the maximum local slope. Precipitation (mm) is also presented as vertical bars.

2.6. Noninterferometric GBSAR Monitoring

The authors of [24,25] 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, and so on. 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 noninterferometric GBSAR approach. In this period, eight measurement campaigns were carried out using the IBIS-L Ku-band GBSAR (Ingegneria Dei Sistemi S.p.A., Pisa, Italy, 2010; Figure 18). In each campaign, 15 small CRs (Figure 19) were deployed in and around the target area (11 inside, 4 outside as reference).

Figure 18. Picture of the IDS GBSAR system. The synthetic aperture is obtained through the movement of the radar sensor (yellow box) along the rail.

Figure 19. One of the small Corner Reflectors deployed over the landslide lower unit in order to fix up the vegetation and snow problems. The operator is holding a surveying circular prism, which is observed from a reference point with a Total Station, for validation purposes.

In parallel to the GBSAR measurements, five Total Station 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 (Figure 20); the movement of the points almost *en bloc* corresponds to a translational landslide.

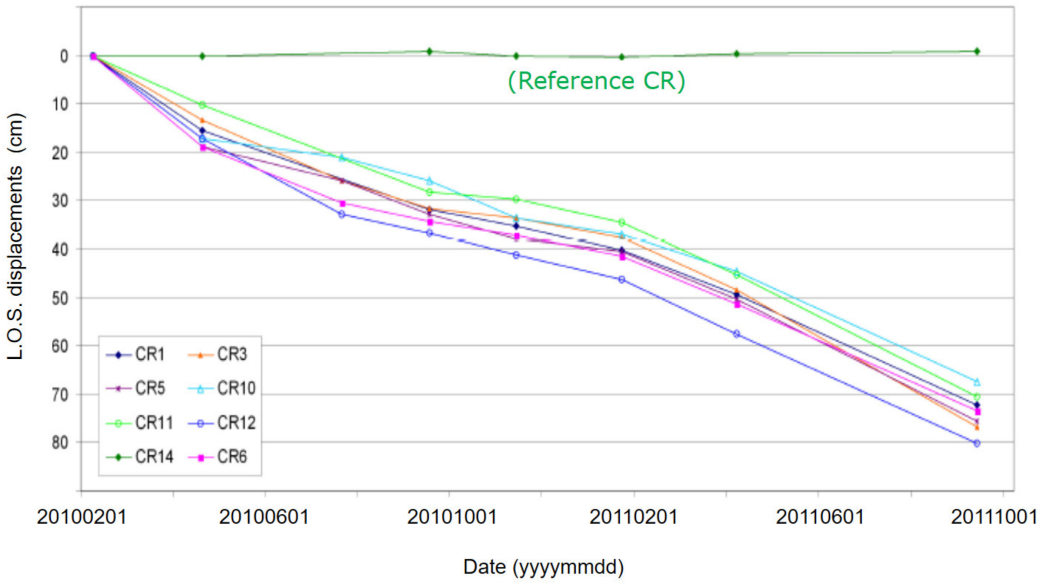

Figure 20. L.O.S. displacements measured with noninterferometric GBSAR between February 2010 and September 2011 at eight small CRs. The CR14, in a stable zone, acts as reference CR.

3. Discussion

As the different systems were applied to certain common points, the resulting displacements could be compared, and practical data, including advantages and drawbacks, could be derived.

For the superficial methods, we observed that the GPS measurements showed better trends and stability than the Total Station measurements, at least with the Vallcebre conditions and equipment. An example is given in Figure 21. Moreover, the GPS surveying is "all-weather" in practice, which is an additional advantage when working in mountainous areas. A theoretical composition of errors, along with independent checks of the GPS-RTK results obtained at fixed stable points, let us establish the following standard deviations [5]: 16 mm in the horizontal plane and 24 mm in elevation. The GPS network in Vallcebre is still in use.

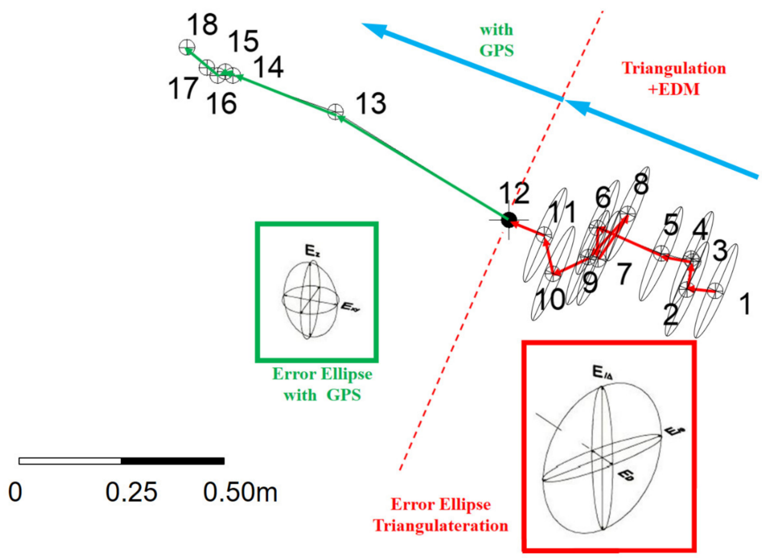

Figure 21. Apparent change in the behavior of point G2 when monitored with classical surveying (dots 1 to 12) or with GPS (dots 12 to 18). The insets with the error ellipses for both systems show a more balanced and better precision for the GPS measurements. Blue arrow points towards the Total Station.

The GPS measurements were also used to check inclinometer and wire extensometer displacements at several boreholes [4]. As an example, in Figure 22, 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. Nevertheless, the wire extensometers and GPS measurements have been continued without trouble beyond these figures.

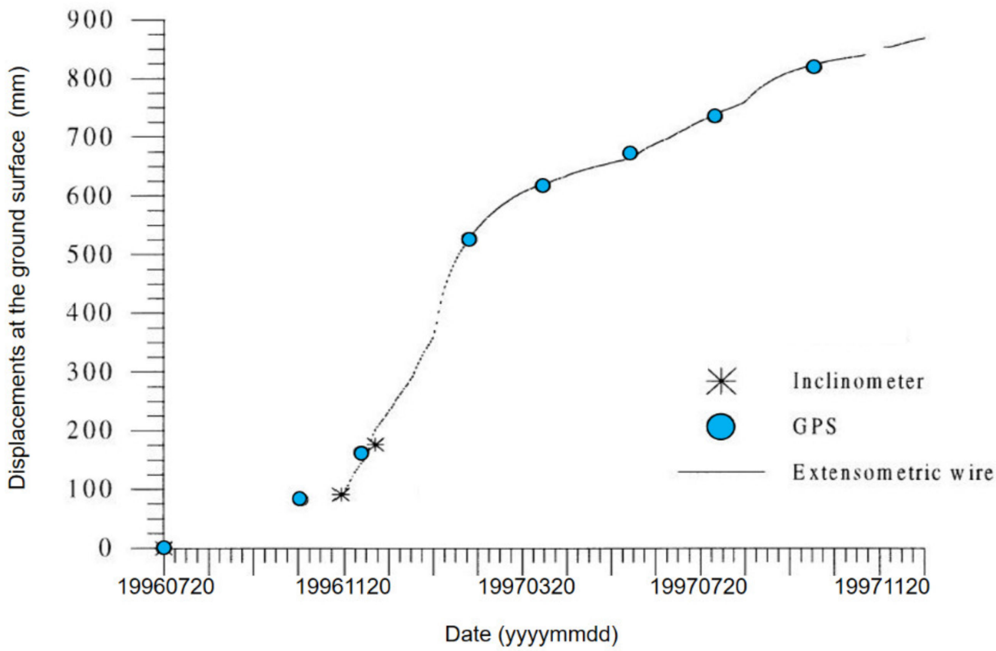

Figure 22. Comparison of the corrected wire extensometer displacement (D_h) against the GPS and the inclinometric measurements of the Vallcebre borehole S2.

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 ΔZ as well as the ΔDistance. It is worth noting that the GPS can also be installed and operated in continuous (see [18] for instance).

Cross-checking was also useful for the radar measurements, validating or improving the remote sensing techniques. Every GPS campaign included the CR and the borehole heads (Figure 23). For instance, in Figure 24 a phase unwrapping problem is recovered. The figure shows two displacement time series of CR_4. 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 (green curve), which is located relatively close to CR_4. It is interesting to compare the time series of CR_4 (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 CR_4 curve. The curves do not fully overlap because one point is 84 m from the other.

Figure 23. Cross-checking between techniques: every GPS campaign included the CRs (CR_2 in the picture) and the top of the boreholes where the wire extensometers and/or the inclinometers were installed.

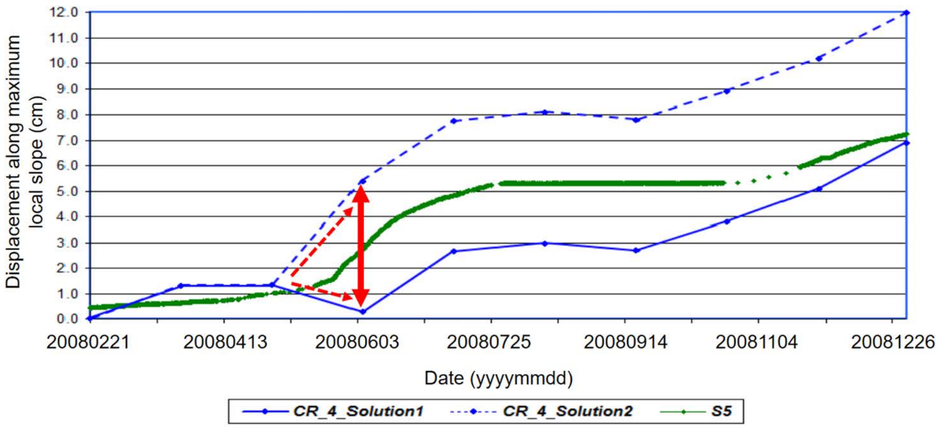

Figure 24. Displacement time series estimated with DInSAR over the CR_4 Corner Reflector, and measured by the wire-extensometer S5, located at a distance of 84 m. A DInSAR ambiguity is shown in red.

The GBSAR amplitude technique presented in Section 2.6 was also validated against the continuous monitoring given by the wire extensometer system. Prior to performing a proper comparison, the CR5 and CR7 Line-Of-Sight (L.O.S.) results (Figure 20) has to be projected onto the total displacement vector (estimated from GPS measurements in the area). The method can be found in [7] and is outlined in Figure 25.

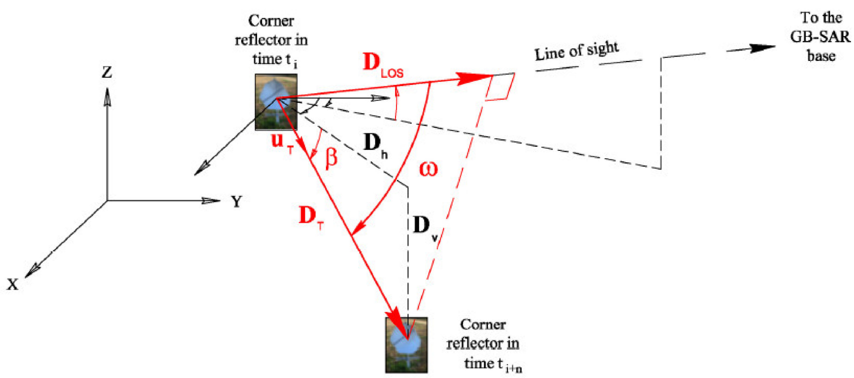

Figure 25. The GBSAR total displacement, D_T, is computed from D_{LOS} using the 3D average direction derived from GPS (unit vector U_T) [7].

After the projection, the CR5 and CR7 GBSAR displacements can be compared with the closer wire extensometer (S11 and S2 respectively, Figure 26). Dashed straight lines have a 1:1 slope, i.e., the perfect fit, which is almost reached.

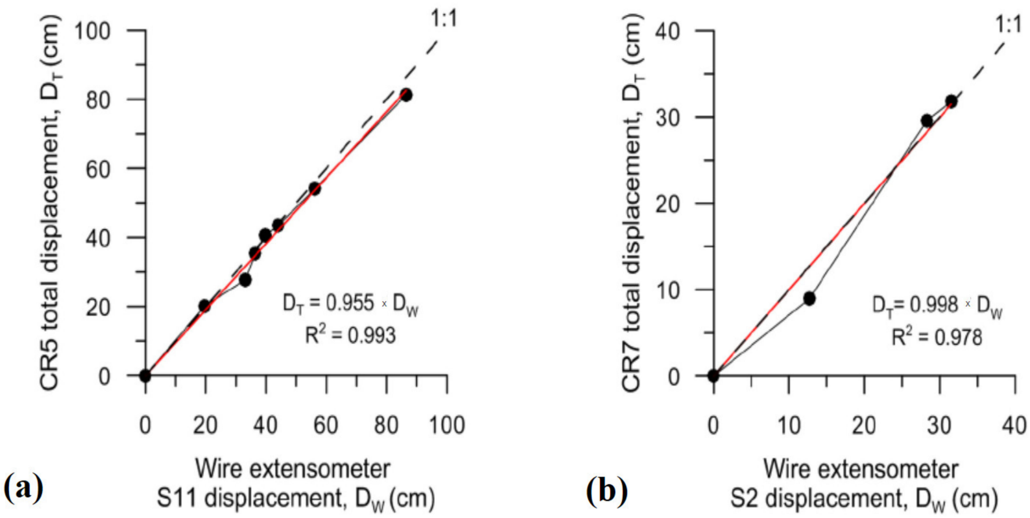

Figure 26. Charts showing GBSAR total displacement, D_T, against wire extensometer displacement, D_W: (**a**) for CR5 and S11, and (**b**) for CR7 and S2.

Finally, after all this precision considerations and system crosschecks, the SAR and/or cable displacements can be visualized as 3D vectors, the 3D direction is given by the GPS data (Figure 27). This overall presentation of the results for the landslide lower unit, with 15 displacement vectors, show a displacement pattern corresponding to a very orthodox translational landslide, with a fair general trend towards the NW, and a small gradient (increase in rate) when approaching the torrent.

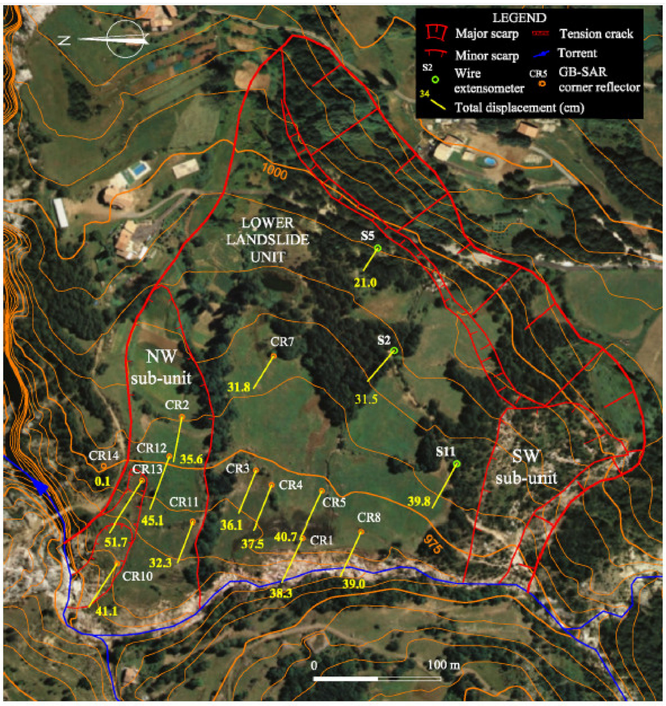

Figure 27. Displacement field of the lower unit of the Vallcebre landslide reconstructed using GBSAR CRs and borehole wire extensometers (S). The yellow figures, in cm, are the total displacements observed from February to November 2010 [7].

4. Summary and Conclusions

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, along with the full formulation, validation and conclusions, can be found in [1,4–7]. To conclude, we present here some lessons learned during the progressive monitoring of the Vallcebre landslide since 1987.

A summary of the main characteristics of the methods is given in Table 1. This table is in accordance with [5,9], 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 'Precision' figures seek to characterize the 'real' or field performance of the systems in our landslide instead of the theoretical values that can be found in the instrument's technical specifications. The latter were determined in lab conditions and were found to be too optimistic, in general. The 'Complexity' column aims to quantify the refinement of the equipment and personnel involved, and the 'Cost' column includes the amount of instrumentation, installation and work needed to obtain the data.

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 [b]
	EDM& Theodolite	Δdist. or $\Delta X,\Delta Y,\Delta Z$	15 to 1500 m	7 mm for Δdist, >25 mm for the rest	Medium	Low	Practical experience in surveying is needed [c]
	GPS [d]	$\Delta X,\Delta Y,\Delta Z$	800 to 2300 m	12–16 mm (horiz.) 18–24 mm (elev.)	Low	Low	Discontinuous over time [c]
	CR based DInSAR	Displacement L.O.S.	Non applicable	a few mm	High	High	Each 35 days with Envisat
	Noninterferometric GBSAR	Displacement L.O.S.	500–800 m	below 1 cm	High	High	Continuous. CRs must be installed each campaign
	Distributed Fiber Optics (in trench) [e]	Zones with strain changes	Non available	Non available	High	High	Not installed yet
In-hole	Inclinometer	$\Delta X,\Delta Y$	15 to 45 m depth	1 to 2 mm	Low	Medium	Discontinuous over time [c]
	Wire extensometer [d]	$\Delta D_{wire} \rightarrow \Delta D_{horiz}$, ΔD_{vert}	15 to 45 m depth	0.5 mm in the wire length [a]	Low	Medium	Continuous log, discontinuous/continuous download
	Piezometer [d]	$\Delta Pw \sim \Delta Hw$	15 to 45 m depth	30 mm water head	Low	Low-Medium	Continuous log, discontinuous/continuous download

[a]: Wire extensometer. After calibration of the wire equation, 2 mm in the surface displacement can be achieved. [b]: The application of Terrestrial or Low-aerial photogram. is becoming easier because of drones and VSfM based SW. [c]: The technique, with a slightly different setup, may become continuous (continuous GPS, Robotic Total St., In-Place-Incl. [d]: GPS, Wire extensometer and Piezometer are green because they are still operational. [e]: Distributed Fiber Optics is red because it has not yet been applied.

The methods in the table should not be considered as excluding alternatives, but rather, as complementary systems to be applied progressively or in different areas, as has been explained in Section 2. For instance, the photogrammetry was used in the toe of the slide to monitor a fairly small but very active area. EDM and triangulation (and later the GPS) were implemented to cover the whole hillside and capture mean movements as big as 1 m 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. As stated in note 'c' in Table 1, although not implemented in Vallcebre, it is technically possible to automate the procedure for the continuous monitoring of the displacements.

On the other hand, the GPS results helped to calibrate the parameters of the wire extensometer equation [4]. The installation of these in-hole devices was possible only when additional funding was obtained in order to drill the boreholes and instrument them. The inclinometers and the in-hole wire extensometers complement each other very well. As the landslide was fairly active, the inclinometers had a short 'life', but produced high-quality information on landslide displacement profiles, velocities and the position of the shear surface quite immediately after their installation. In contrast, at the early stages of deformation, the wire extensometers may only record negative displacements, which are not easily related to the superficial ones. However, once the inclinometers were lost, the wire extensometers provided continuous recording, even for very large displacements. Since 1996, when they were first installed, the wire extensometers have provided a measurement readout each 20 min; 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 (Figure 14), 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 center of the landslide in order to get the significant precipitation, because the rainfall may vary sharply from one point to another.

Redundancy between methods is advisable in case of malfunctions in the devices or as a means to cover gaps in data. As shown in the previous sections, all the results are in fairly good accordance when adequate corrections are applied (Figures 22 and 23). Prior to the comparison of the different techniques, some error considerations must be made, in particular, the filtering of any systematic errors (Figures 24 and 25, for instance). In order to 'automatically' filter some systematic errors, during the monitoring operation (acquisition and data handling) it is convenient to be very 'systematic' (to follow exactly the same field and processing procedures).

Contrary to structural monitoring, when working with natural materials like soils and rock, we have to accept natural variability. To address this variability, it is better to apply continuous techniques, both in the time and spatial domains, i.e., the two axes presented in Figure 28. It must be highlighted that the tentative classification of the different techniques in the figure (time frequency/spatial resolution) corresponds to the Vallcebre landslide implementation as reflected in this paper; other setups could be adopted at Vallcebre and other sites. The actual installation depends not only on the site, but also on the level of risk and the available budget.

The systems that were operated continuously relies on automatic acquisition. We learned that 'automatic' does not means 'free of maintenance'. On the contrary, the continuous systems need continuous surveillance and maintenance [2]. Another recommendation for long-term monitoring networks is that, when feasible, it is better to avoid points or benchmarks that may exhibit their own movements (large boulders, light poles, trees, concrete pillars, old stone walls and so on). The discreet marking of points diminishes natural disturbance and vandalism. Finally yet importantly, it is mandatory to include within the network several fixed points in stable areas around the landslide for verification purposes.

Over the years, some improvements in the electrical supply (solar panels) and data transmission (remote download) have been introduced in the Vallcebre setup. Currently, wire extensometer and the piezometer readings can be downloaded from a remote location by means of the mobile phone network.

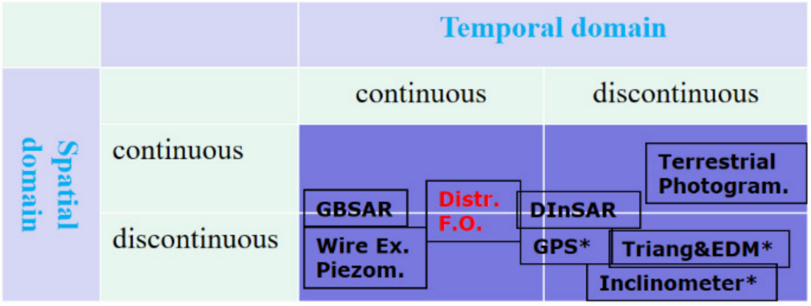

Figure 28. Tentative disposition of the different techniques as specifically used in Vallcebre: following [26], systems are classified according to their continuity in the Spatial and Temporal domain. Distributed Fiber Optics is in red because it has not yet been applied. The asterisks indicate that the technique, with a slightly different setup, may become continuous over space or time.

All the works described in this paper are capable of qualifying the Vallcebre landslide as a real-scale "in situ" lab or observatory. The relatively slow rate of motion and the sustained long-term mobility make it suitable for the testing and validation of several new systems within the frameworks of European and National Projects. In the near future, we plan to install an experimental array of distributed fiber optics [27] in order to assess its field performance. The projected array includes around 600 m of FO buried in a trench besides a country road, roughly along the 1000 m contour line shown in Figure 27. This area is subjected to shear displacements produced by the landslide lateral limits and the transition from the middle to the lower unit. The wire extensometer and the GPS control points present in the zone will permit the cross-calibration of the FO array results and performance.

Basic research on the performance of the different instruments and methods that have been applied in the Vallcebre landslide should help to choose a monitoring strategy in new sites. In making such choices, we must bear in mind that the monitoring must address some fundamental geotechnical questions [28,29]. Instruments and methods that help to answer these questions should be selected. As John Dunnicliff stated, "If there is no question, there should be no instrumentation".

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