

EVOLUTION OF TECHNIQUES FOR MONITORING UNSTABLE SLOPES

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EXTENDED ABSTRACT

Il monitoraggio di aree instabili o potenzialmente instabili è un'operazione necessaria ogni qualvolta non sia possibile rimuovere o mitigare con interventi di riduzione della pericolosità le condizioni di rischio associate al fenomeno di instabilità paventato. In questi casi, infatti il monitoraggio rappresenta un'azione di mitigazione molto importante, condotta utilizzando strumentazione e tecniche di indagine tradizionali. La strumentazione convenzionalmente utilizzata per il monitoraggio di versanti in frana, come ad esempio gli inclinometri, estensimetri o gli strumenti di controllo topografico, consente di definire, se posizionata correttamente e dotata di adeguata accuratezza i valori di spostamento (profondo e/o superficiale) e le loro variazioni nel tempo, rendendo così possibile il controllo della velocità di spostamento dei singoli punti e soprattutto dell'accelerazione all'interno dell'area in frana. È rilevante, infatti, ai fini di una valutazione anche solo qualitativa del tempo di occorrenza della fase parossistica dell'evento di instabilità, il controllo delle accelerazioni delle masse coinvolte, in quanto immediatamente riferibili a variazioni in negativo dell'equilibrio dei sistemi di forze agenti. Peraltro, la resilienza dei sistemi sotto deformazione è sensibilmente ridotta, in particolar modo in termini di velocità di progressione dell'evento di instabilità, in presenza di materiali rigidi e/o fragili. I metodi convenzionali nella maggior parte dei casi non consentono di acquisire informazioni in tempo reale. Tecniche di monitoraggio in *remote-sensing*, quali laser-scanner, LiDAR o InSAR, sono in grado di analizzare un versante instabile con elevata frequenza spaziale e temporale di acquisizione dei dati; di contro, consentono unicamente misure di spostamento superficiale. L'evoluzione tecnologica recente, esportabile al campo del monitoraggio dei fenomeni di instabilità dei versanti, è particolarmente vivace e ha consentito negli ultimi anni l'utilizzo di sistemi di controllo e allarme impensabili qualche decennio fa, anche in ragione di una sensibile riduzione dei costi della sensoristica.

Le più importanti innovazioni derivano dall'adozione di tecniche di misura "non a contatto", che hanno sviluppato le tecniche di telerilevamento, anche da distanze satellitari, mediante le quali è possibile controllare l'umidità del suolo da satellite e, sempre da satellite, misurare spostamenti piccolissimi mediante immagini RADAR.

Nuove tecniche di misura si sono sviluppate, intendendo con tale termine "l'assegnazione di un valore numerico nella opportuna unità di misura e con il corretto numero di cifre significative ad una grandezza fisica in un specifico intervallo temporale" che è quello necessario all'effettuazione della misura. Questi intervalli temporali sono diventati estremamente ridotti, cioè, in termini tecnici, le frequenze di campionamento per alcuni strumenti sono diventate elevatissime, con due ulteriori importanti conseguenze: 1) possibilità di compensazione in tempo reale (per quelle che sono le necessità dell'utente) di alcuni tipi di errori casuali; 2) disponibilità istantanea di una misura, più correttamente definibile come "informazione istantanea di un processo relativo ad una procedura di misura fornita da un trasduttore o da un sistema", cioè, in un'acquisizione multipla nel tempo e con trasmissione dell'informazione all'utente finale, anche a distanza dal punto di rilevamento, ma in tempo reale, attività meglio nota come "monitoraggio".

Esiste una differenza fondamentale tra una misura di processo, ad esempio il controllo dello spostamento nel tempo di uno o più punti di un corpo di frana o di un'area instabile, la misura delle variazioni della superficie piezometrica, ecc, ed il monitoraggio. La trasmissione dell'informazione in tempo reale relativa ai parametri che caratterizzano il processo, cioè il monitoraggio, presuppone una fase prodromica a quella successiva e necessaria di analisi finalizzata ad una decisione. Cioè, il fenomeno procede secondo le aspettative ed in contesto sicuro ed accettabile, analisi da cui non scaturisce alcuna azione, ovvero il processo ha subito variazioni che definiscono cinetiche not safe, da cui discendono azioni immediate tese alla mitigazione del rischio.

Parallelamente alla diffusione delle nuove tecnologie supportate da strumenti sempre più performanti, si afferma anche qualche disinformazione o mito o più semplicemente cattiva informazione, onde si assiste spesso all'uso improprio delle nuove tecnologie.

È utile osservare anche che generalmente può non interessare la precisione o l'accuratezza della misura diretta, quanto quella della sua variazione. In una frana, per esempio, può paradossalmente non conoscersi la distanza di un punto osservato su di essa, soprattutto se osservata da distanza; ma è sicuramente necessario conoscere la sua variazione con accuratezza adeguata al problema in esame, cioè alla natura dei materiali (terreni o rocce) coinvolti ed alle loro rigidità.

ABSTRACT

The monitoring of unstable or potentially unstable areas is a necessary operation every time you cannot remove the conditions of risk. So, in these cases landslide monitoring represents a very crucial mitigation operation, that is usually done by using conventional investigation devices. Generally, traditional landslide monitoring technologies, such as inclinometers, extensometers, LVDT and TDR based instrumentations, permit to define, if correctly positioned and with adequate accuracy, the critical values of displacement and/or acceleration into landslide body. In most cases, they do not allow real time warning signs to be generated, due to environmental induced errors. Remote-sensing monitoring instruments, such as 3D laser scanner, LIDAR and InSAR, are capable of inspecting an unstable slope with a high spatial and temporal frequency, but allow solely measurements of superficial displacements and deformations. The technological evolution exportable to the field of land instability monitoring is particularly lively and allows the use of warning systems unthinkable just few years ago.

KEYWORDS: *landslide monitoring, remote sensing, TDR, inclinometric system, laser single-beam, acoustic emission*

INTRODUCTION

Starting from the second half of the 20th century a very fast technological growth, deriving from the invention of the semiconductor at the solid state, from their miniaturization and from the progressive cost reduction has revolutionized the techniques for measurement of physical quantities and phenomena. The most important innovation derives from the use of “not-contact” measurement techniques by the remote-sensing instrumentations, such as the control of the soil moisture and temperature, and the measure of displacement by satellite through radar images.

In this context, measure is intended as “the assigning a numerical value in the appropriate measure unit and with the correct number of significant digits to a physical quantity in a specific temporal range”.

The measurement temporal intervals have become very short; the sampling frequencies for some instruments have become very high, with two important consequences: a) the possibility to compensate, in real-time, certain types of random errors; b) the real-time availability of a measure, more correctly definable as “instant information about a process regarding a measurement procedure provided by a device or a system”; this type of measurement, better known as “monitoring”, allows a multi-temporal acquisition of data and a transmission of information to the final user, even away from the point of detection, but in real-time.

There is a fundamental difference between a “process measure”, such as the registration of the temporal evolution of the displacement of one or more unstable points, the measurement of

groundwater table changing, etc., and the monitoring.

The real-time transmission of information on a parameter characterizing the process requires, before the analysis, a preliminary decisional phase. This means that if the process undergoes changes that define not safe situations, immediate actions aimed at risk mitigation have to be carried out. It is important to highlight that, in some cases, it is more useful to evaluate the variation of the direct measure than its precision or accuracy. For example, in a landslide body, it is necessary to measure the distance variation of one or more points between a measurement device and a target rather than the distance value.

The unstable areas monitoring, aimed at measuring the displacement rate of landslides, in their different portions (feeding area, main body, accumulation area, etc.), allows to evaluate the evolution of the equilibrium conditions and to estimate, preliminarily, the occurrence time of landslides (return period). Therefore, the measurement of landslide displacements is preliminary for assessing the landslide risk and, for this reason, constitutes a risk mitigation operation.

The prediction of the failure phase is one of the most important issue when assessing and mitigating the hazard related to large landslides. Forecasting the failure of a large instable area is difficult task involving the evaluation of a large number of interrelated variables and factors (PELLICANI *et alii*, 2014), such as geometrical and geological complexity, the non-linearity of the time-displacement relationships and seasonal effect (CROSTA & AGLIARDI, 2003).

Monitoring of landslides is usually done in order to estimate alert threshold values of displacement or velocity.

In general, an efficient monitoring system should allow to define:

- a) surface extension and volume of landslides;
- b) the current movement and their spatial and temporal variations;
- c) the dependence of the movements on changing of weather and hydraulic conditions;
- d) the influence of external factors not directly related to the landslide (eg, earthquakes, rainfalls, etc.).

In this paper, the Authors analyze different techniques of landslide monitoring and highlight their application fields.

LANDSLIDE MONITORING SYSTEMS

Monitoring represents the main tool for carrying out evaluation procedures and criteria for spatial and temporal landslide forecast. The forecast of landslide behaviour depends on the possibility to identify either evidences of activity (displacement, velocity, volume of instable mass, direction of displacement, and their temporal variation) or triggering parameters (rainfalls) (TAMBURINI & MARTELLI, 2006). A reliable forecasting method by means of critical (threshold) values of selected kinematic parameters (e.g. displacement, acceleration, etc.) is therefore needed as part of an

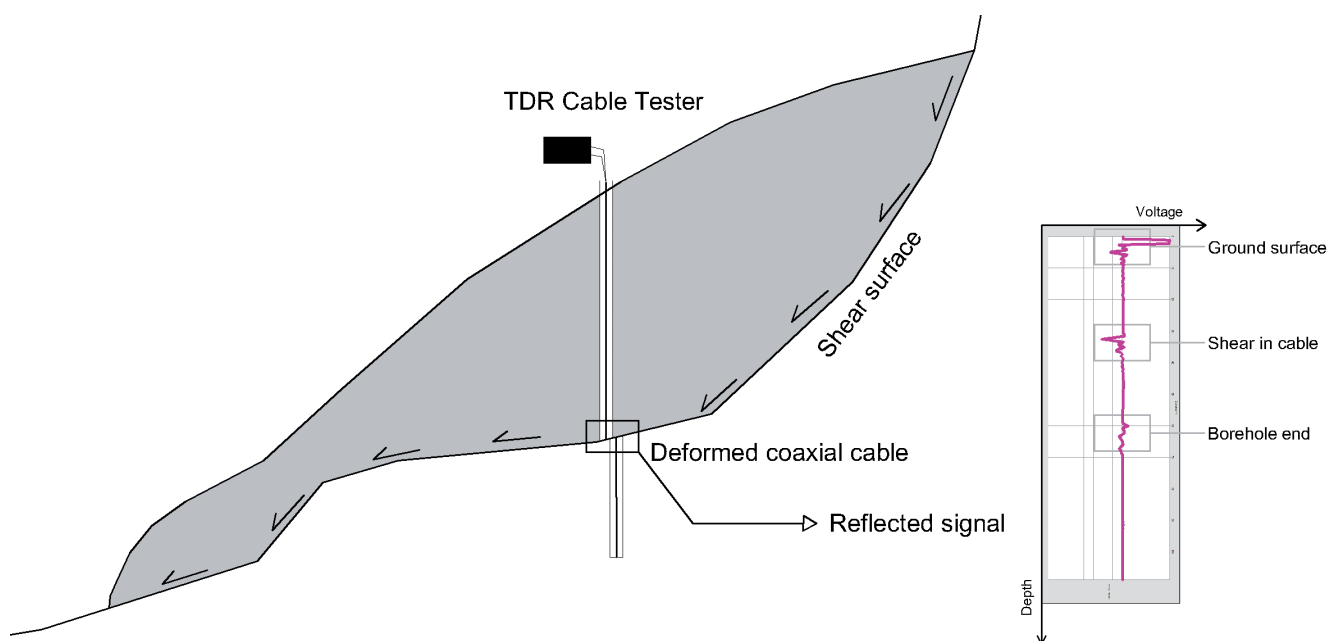


Fig. 1 - TDR installed in a drilled hole

emergency plan.

In literature, many comparative analysis of monitoring systems such as inclinometers (INTERNATIONAL SOCIETY FOR ROCK MECHANICS, 1977), TDR cables, extensometers, GPS benchmarks networks and airborne and ground-based InSAR methods, airborne LIDAR sensor and terrestrial laser scanner have been carried out (ALBA *et alii*, 2005; CORSINI *et alii*, 2005; AROSIO *et alii*, 2009).

Conventional landslide monitoring system

Traditional landslide monitoring systems include those techniques for the direct measurement of the spatial and/or temporal evolution of landslide processes.

Geotechnical instrumentation (consisting of inclinometers, wire and surface extensometers, TDR cables, etc.) allows the characterization of slope behaviour. By using of these techniques, with support of GPS benchmarks networks, it is possible, if the position and distribution of the measuring points have been correctly chosen, to obtain deep and superficial displacement field and to derive the slope geometry (volume of instable mass).

The main problem of inclinometers is that these devices, if installed in landslides with relevant displacements, can failure also in short time. The use of Time Domain Reflectometry (TDR) in slope monitoring is very useful for detecting and real time transmitting information about points of strain anomaly generated inside the landslide body. A complete TDR landslide monitoring system generally consists of coaxial cable, TDR, data loggers, remote communications equipment, data analysis software and so on (Fig. 1). The principle of TDR is similar to the Radar. Drill a hole

in the slope to be monitored, place coaxial cable in the borehole, and then prime the borehole with the sand mixed concrete to make coaxial cable combine with the surrounding rock close closely. The electric pulse signal excited by TDR time domain reflectometry transmits from the surface down along the coaxial cable, the displacement and deformation of slope will make coaxial cable fracture or deformation, which lead to a change in impedance of coaxial cable, resulting in reflected pulse signal (GUO *et alii*, 2010).

Furthermore, by using of piezometric probes it is possible to obtain information on groundwater conditions. All these measurements allow to define a physical model of slopes useful for slope stability problems. Regarding to water level measurements, the current common used transducers allow to measure the water pressure and not the geometric distance of the water table from the ground surface. Among the traditional methods for landslide monitoring, also techniques for pluviometric thresholds detecting are included. Generally, the analyses of rainfall data, if coupled with the displacements and surface rates of landslide body, highlight, albeit with attenuation and/or delays, the accelerations or reactivations of the unstable processes during particular rainfall events (PELLICANI *et alii*, 2016). The geotechnical survey techniques provide reliable results if applied to slopes constituted by loose soils, while they have some limitations when applied to rocky slopes, since the process which leads to failure is different.

In the field of the deep displacements monitoring systems, the Turin Research Institute for Hydro-Geologic Protection of the National Research Council (IRPI CNR) developed the

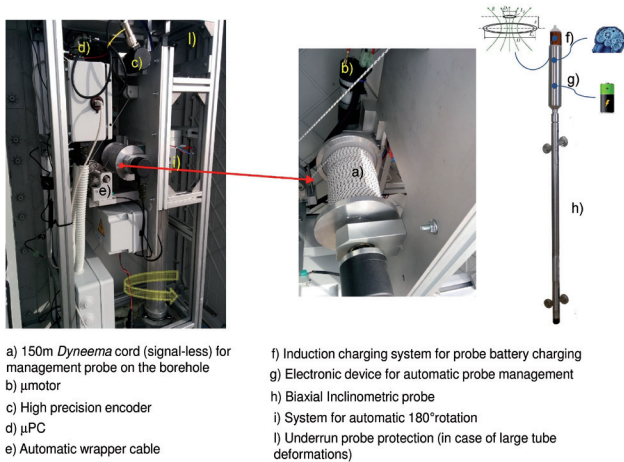


Fig. 2 - Automated Inclinometric System (AIS) installed in a standard fiberglass casing

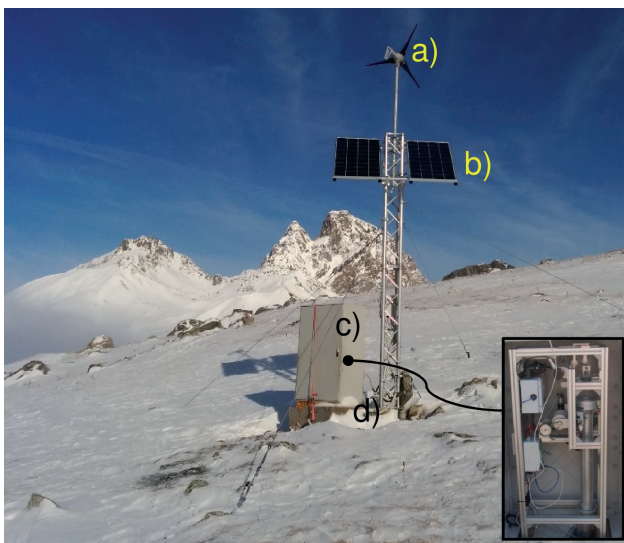


Fig. 3 - Example of AIS installation on the Portalet landslide (Pyrenees) at 1800 m high Lampre European Project [a) Wind turbine, b) Solar panels, c) AIS system, d) Backup battery]

Automate Inclinometer System (AIS) (Fig. 2 and 3) in the early 1990s with the objective of automatically performing the traditional inclinometric measurements (LOLLINO, 1992). The early experimental versions of the AIS immediately showed the high potential of the system that corresponds to:

- high accuracy and repeatability of measurement;
- complete and continuous plot of the inclinometric tube (measurement step 0.5 m) (Fig. 4);
- sliding surfaces recognition;
- accurate and complete measurement of the velocity and acceleration of the phenomenon monitored and possibility to correlate the displacements with other landslide typical parameter (water table level, rainfalls etc.) (Fig. 5 and 6)

(LOLLINO *et alii*, 2001; LOLLINO *et alii*, 2002; LOLLINO *et alii*, 2003; LOLLINO *et alii*, 2006);

- possibility of reusing the instrument even following increased deformations of the inclinometric tube (cutted tube after big landslide deformation).

In the 2008, following the development of new technologies, a new version of the AIS has been designed and produced (LOLLINO *et alii*, 2008). The system is characterized by an electromechanical system able to perform inclinometer measurements automatically (in both faces 0° , 180°). The equipment, managed by an electronic low consumption system, is composed of a biaxial inclinometer probe (servo or MEMS type) and by an electric motor with precision encoder, for handling and continuous control of the position of the probe within the tube. With the schedule system, the probe is able to go down periodically in the inclinometer tube and go up with stops (0.5 meters typically) for the execution of the normal measures of deviation from the vertical. The inclinometer probe is directly connected with an innovative battery electronic device can store and manage data without the traditional electrical connection. Therefore, the probe is connected to the system by a Kevlar cord (2.5 mm diameter) just for the mechanical support. At the end of measurements, data is transferred wirelessly (868 MHz) and the battery charge is provided by a contact-less inductive coupling.

Remote-sensing landslide monitoring

Remote-sensing monitoring systems include those techniques that allow to measure, remotely, geometric changes, deformations or displacements of a rock slope surface. The main devices used for this purposes are: Total Stations, Terrestrial Laser Scanners, Light Detection and Ranging sensors (LIDAR), Interferometric Synthetic Aperture Radar (InSAR) and Differential-InSAR sensors (D-InSAR).

Total Stations can measure the 3-D coordinates of a point through direct reading of horizontal and vertical angles combined with a range-finder for the measurement of distances. This device can work on the basis of two different techniques: the first one is based on the “phase-shift” evaluation of electromagnetic carrier wave returns and requires a reflector on the point to be measured; the second is based on the measurement of the “time-of-flight” of a pulsed-laser signal, with the advantage of operating without reflectors, albeit with a minor precision (AROSIO *et alii*, 2009).

The Terrestrial Laser scanners can be considered an evolution of Total Stations that extend the capability from single unspecified points up to a large set of points, some millions of points in very short time, on a given surface (AROSIO *et alii*, 2009). The location of each point in 3D space is calculated by determining the “time of flight” of the reflected laser beam, which is proportional to the distance from the scanner. Combining with the directional parameters of the scanner (azimuth and angle) this gives the location relative to the scanner’s position (SLOB *et alii*, 2002). Terrestrial Laser Scanners

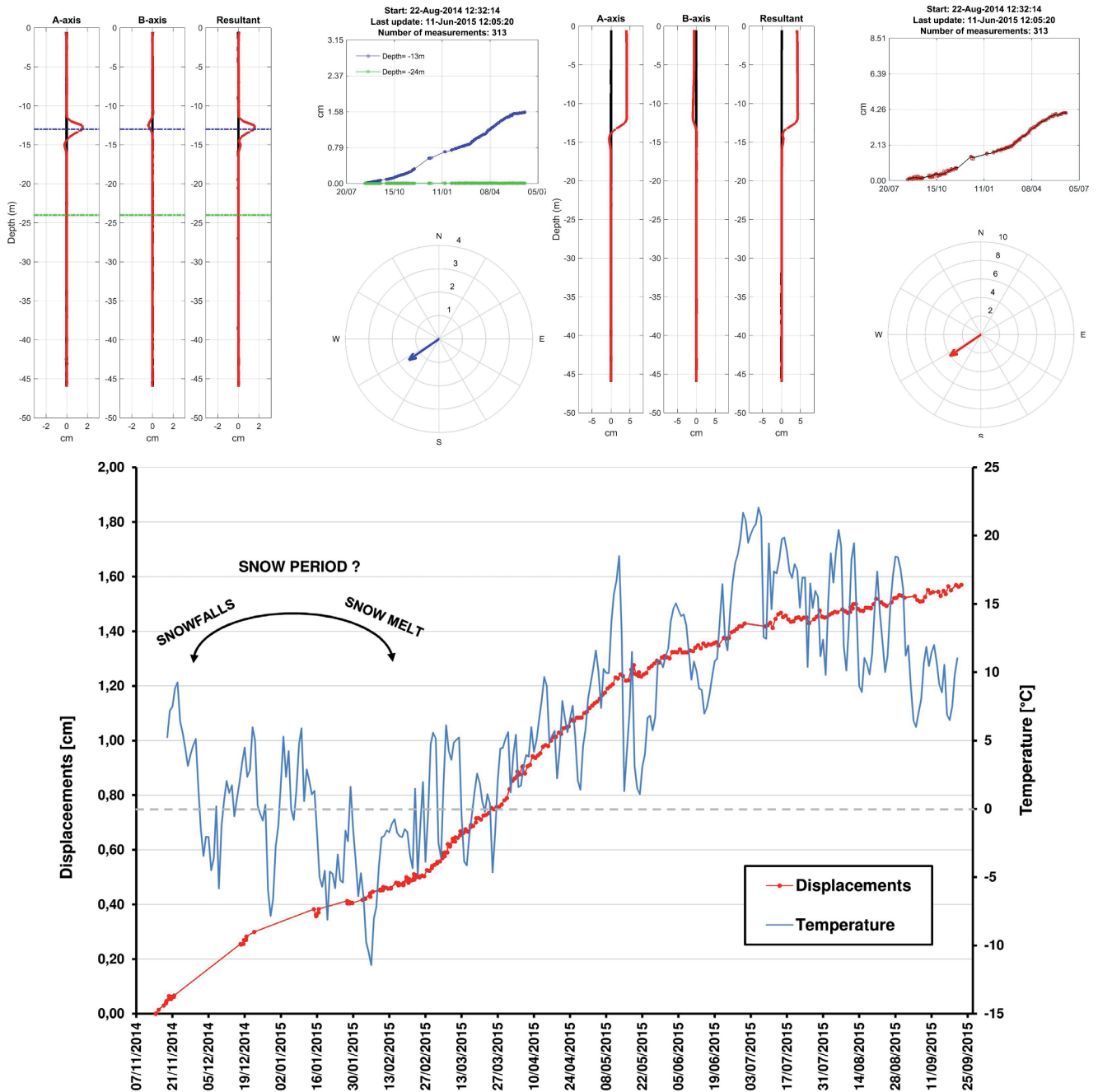


Fig. 4 - AIS results on Portalet Landslide: local (a) and cumulated displacements (b). The near-real time data show immediately the correlation between the rainfalls and snow melts and increase of the displacements (c)

have different application fields, some of them regard:

- analysis of the morphological rock structure, such as distribution and orientation of discontinuities (SLOB *et alii*, 2002; RONCELLA & FORLANI, 2005; FENG & RÖSHOFF, 2006);
- simulation of possible paths of falling rocks for hazard mapping (ALBA *et alii*, 2005);

- monitoring and modelling of instability phenomena (GIRARDEAU-MONTAUT *et alii*, 2005).

Unlike conventional monitoring systems, Laser Scanning allows the high accuracy measurement of a small number of control points. So, TLS can be used to monitor the deformations of rock face or landslides by comparing point-clouds surveyed at

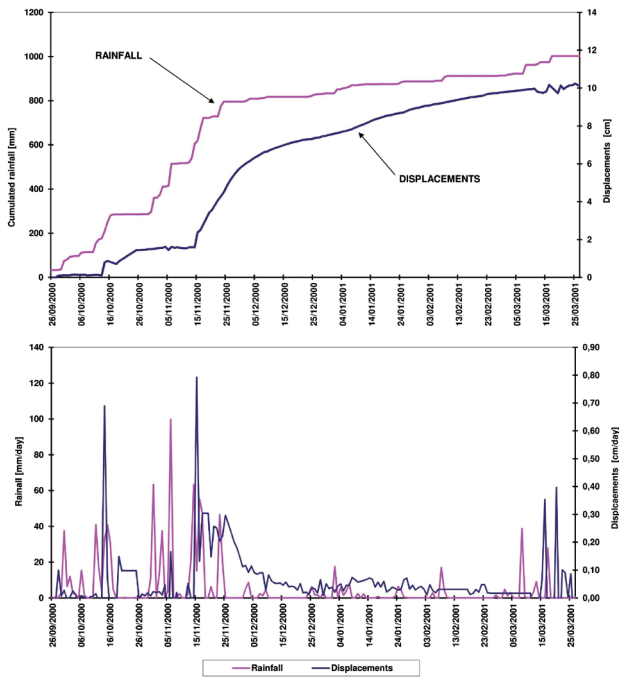


Fig. 5 - AIS results on Cabella Ligure Landslide (LOLLINO et alii, 2002). The obtained results shows the correlation between the peak of rainfalls and the peak of displacements increase (about 9 day delay)

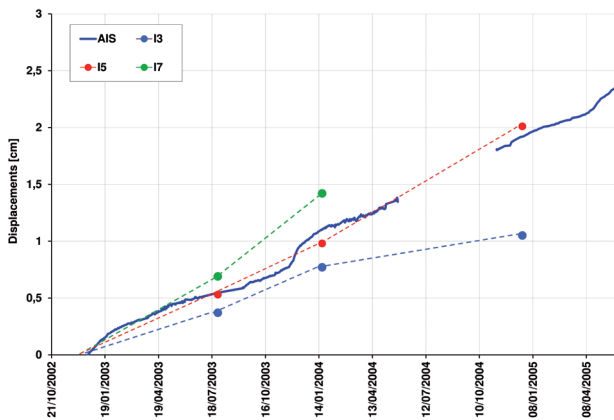


Fig. 6 - AIS results on Cabella Ligure Landslide. The plot shows the comparison results between traditional inclinometer measurements (1 meas/6 months) and AIS results (1 meas/day)

different times. This comparison between multi-temporal point-clouds cannot be carried out point by point, because there is not precise correspondence between points. Furthermore, the intrinsic precision of terrestrial laser scanner does not make it possible to obtain measurements that can detect very small deformation on a rock, such as those anticipating a collapse (AROSIO et alii, 2009).

LiDAR (Light Detection And Ranging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The

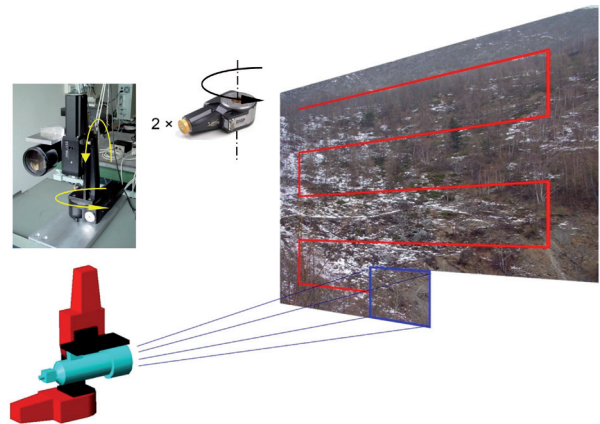


Fig. 7 - Principle of the IDMS processing approach

prevalent method to determine distance to an object or surface is to use laser pulses. Like the similar radar technology, which uses radio waves, which is light that is not in the visible spectrum, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal.

An innovative technique is the Image Detection Monitoring System (IDMS). This is a system developed and patented by IRPI-CNR for the monitoring, in automatic and continuous measuring conditions, surface displacements using optical image processing approach (ALLASIA et alii, 2007; ALLASIA et alii, 2009; ALLASIA et alii, 2012; ALLASIA et alii, 2013; LOLLINO et alii, 2007). This system is a contact less approach that does not need targets, often characterized by the difficulty on their installation and maintenance. These characteristics make a system most flexible allowing to modify the investigated areas without logistic difficulties and without further costs (for adding targets for example). The typical system is constituted by a digital reflex camera (res. > 16MPixel) that, according to different needs, can be combined to a long range reflectorless laser distantiometer (Fig. 7).

To investigate larger areas, the system has a sophisticated mechanism for the handling of SLR camera and the distancemeter. The operation is based on analysis of multi-temporal images that, analyzed through specific algorithms, allows detection of movements of investigated areas. The integration of movements so calculated with the measures of distance, allows to derive the movement of three-dimensional topography in landslides areas. The SLR camera is automatically moved by a high accuracy positioning mechanism managed (pan and tilt) by a low consumption pc. The principle of operation is based on the analysis of a time series of pictures of an area that, processed by pixel offset technics, allow to obtain topographic displacements (Fig. 8).

It is possible to use several algorithm for image processing but the algorithm usually used is based on the analysis of correlation between the phases of the Fourier transform of the two images to compare. The phase correlation is a quick approach to

measure movements between similar images. To minimize any inconvenience due to different shooting conditions (different rightness due to sun/shadow or to the different weather conditions) as usually used Sobel or similar filter. The processing program was divided into two phases: the first configuration of the system during which input is required of an expert for the selection of areas to be monitored. At this stage, for each area of interest are stored their images (Master images), the orientation of the sensor (pan and tilt) and the Fourier transform of its image gradient.

The next phase of the measurement, the sensor is automatically moved at the stored position and a new image is acquired (slave image) and calculated the Fourier transform. With the phase correlation between this and the reference image are evaluated the displacements perpendicular at the Line Of Sight (LOS) and if the correlation is too low the camera is automatically shifted by the rotation devices and a new image are acquired. These implementations, in addition to the freedom from the needs of reflecting targets, increases the system flexibility that can operate in dynamic contexts where the phenomenon morphology can quickly change (Fig. 9).



Fig. 8 - The system used for the landslide monitoring in the Southern of the Italy. In this scenario characterized by high morphological changes due to the excavation, the use of the IDMS allowed to follow the displacements without interference with the excavation works

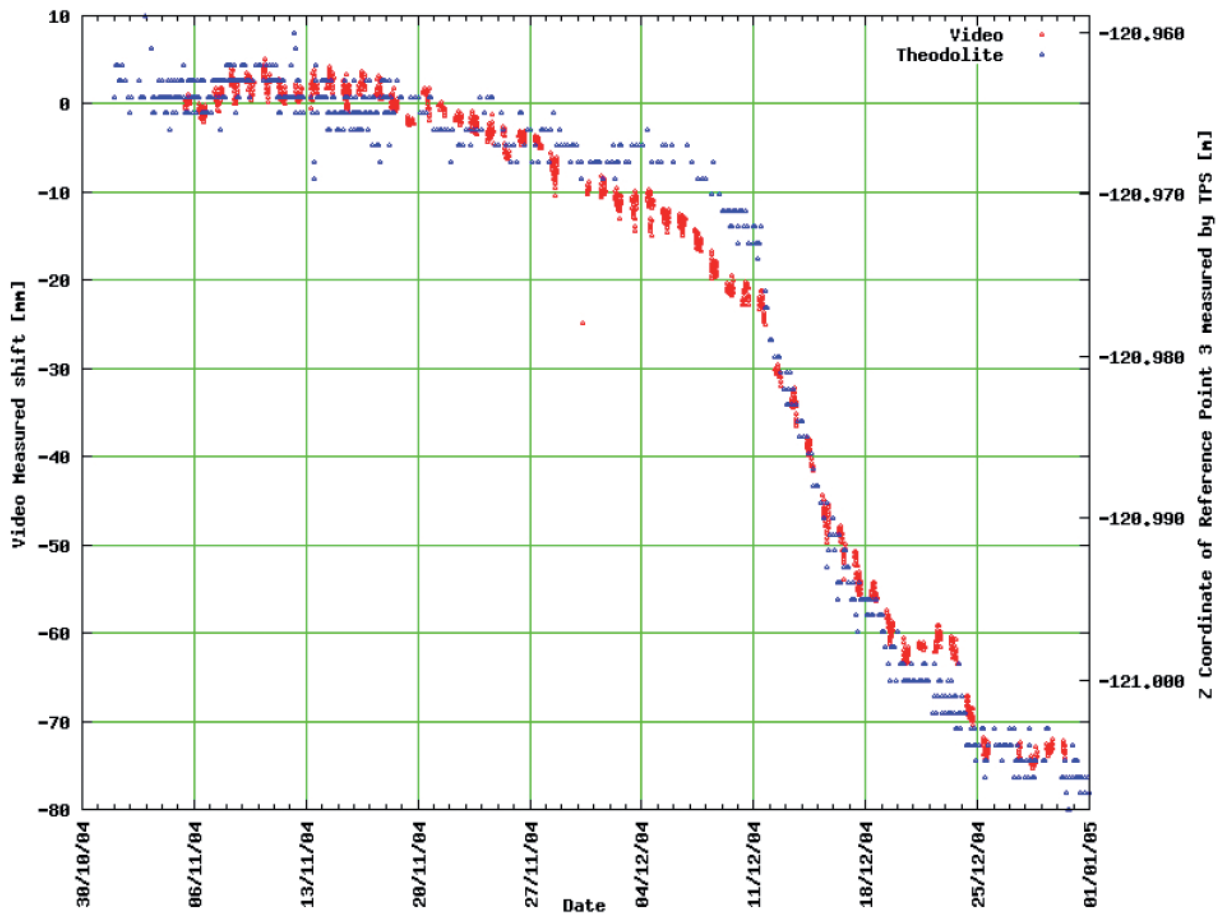


Fig. 9 - Results of the comparisons between Robotized Total Station (blue) and IDMS (red)

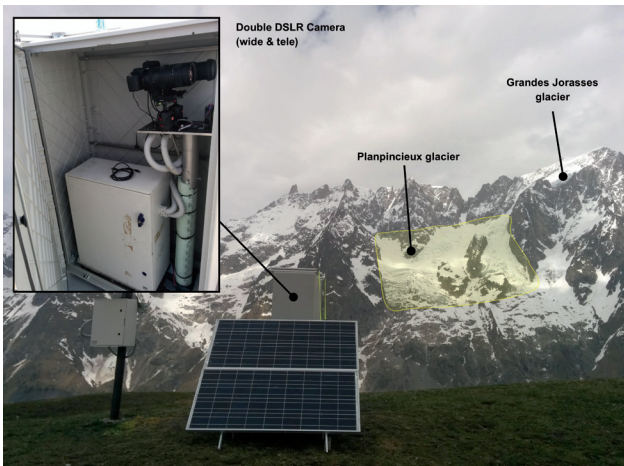


Fig. 10 - Planpincieux Glacier monitoring system. The system, powered by solar panels, is constituted by a Canon EOS 600D SLR Camera e 300 mm tele lens. The average distance is ca. 3500 m and the accuracy is about 5cm/pixel (perpendicular at the LOS)

The system can also be used in a simplified version that not requires the automatic handling system but only the reflex camera. An experimental monitoring station was installed on August 2013 in order to monitor the surface displacements at Planpincieux Glacier (Valle d' Aosta Valley) (GIORDAN *et alii*, 2016) (Fig. 10 and 11). The monitoring station is located on the opposite side of the valley, at the top of the Mt. de la Saxe, ca. 3.5 km away from the target under investigation. Monitoring includes: (i) a surveillance module, based on a medium resolution digital camera, observing large part of the slope; (ii) a photogrammetric module, based on a high resolution digital camera equipped with a 300 mm optical zoom, pointed to the PG front (IDMS simplified version). Digital images acquired by the monitoring station are acquired with a revisit time of 1-hour, and analyzed by considering change-detection and pixel-offset techniques. This approach allows to evaluate surface changes over time, as well as to retrieve quantitative measurements of the glacier displacements.

Regarding to the analysis of stability of slopes affected

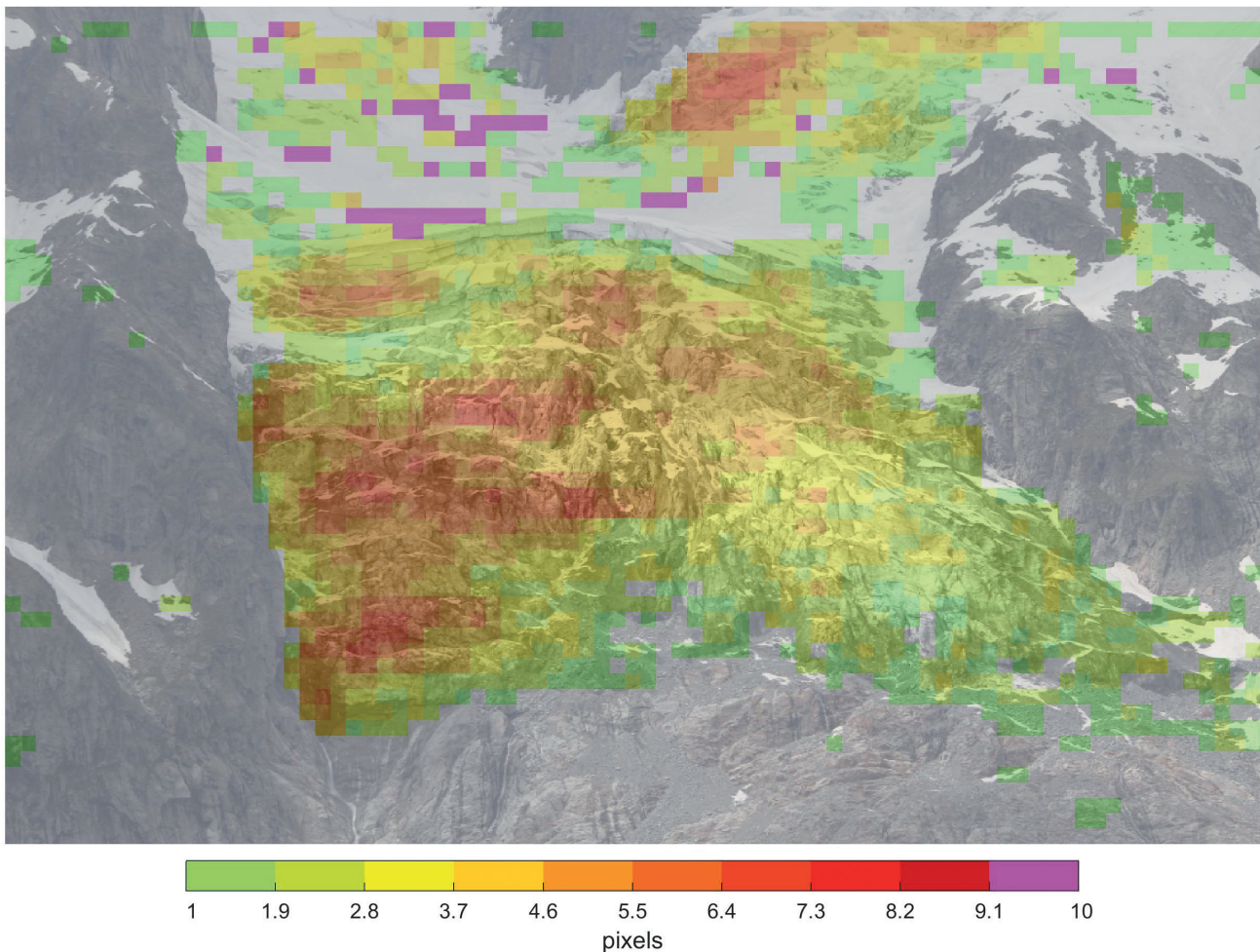


Fig. 11 - Pixel offset result showing cumulated shifts during the period 15 day

by landslides, the SAR remote sensing techniques are very common and used. The SAR (Synthetic Aperture Radar) is a sensor, operating in the microwave range, able to measure the backscattered electromagnetic field generated by the antenna and spread by the ground. This measure is carried out in a coherent way, keeping separate the components in phase and in signal quadrature. Through this separation, it is possible to achieve, for each image resolution cell, an intensity value and a phase value for the electromagnetic field returning from the antenna (backscattering of signal). The interferometric technique uses the phase information for reconstructing, from two or more images, the topography of the illuminated area and any slope movements; this products is called interferogram. The capability of SAR satellite remote sensing to identify diffused deformation phenomena over large portions of territory is well documented in literature (FERRARI & MARSELLA, 2000; ROTT, 2004; MARTINEZ-VAZQUEZ & FORTUNY-GUASCH, 2005; ROCCA *et alii*, 2013). The terrestrial SAR allows, with the same signal travel time, to measure rapid events, adapting the measure frequencies.

In recent years an interferometric technique has been developed for studying the ground deformation due to local phenomena (BOZZANO *et alii*, 2011). It is based on the principle that if, during the time that elapses between the acquisition of images (temporal baseline), the land has been subjected to displacements, the phase information of the interferogram will consist of an additional term, due to the same displacement. This remote sensing satellite technique, known as Differential-InSAR, applies a double difference of phase: the first one for reconstructing the interferogram, the second for eliminating the topographic information. The application of this technique to landslide monitoring allows to assess the ground displacement intensity and direction (CASCINI *et alii*, 2009). Furthermore, by comparing Digital Terrain Models (DTM) obtained by interferometric processing of pairs of image before and after the event, it is possible to reconstruct the volumes involved. The limitations of the SAR technique applied to the landslide monitoring depends on the typology of movement, presence of vegetation, soil moisture and type of soil cover.

Certain types of landslide phenomena do not provide coherent data because of the rapid motion and/or spatial scale: (mud flows, rock falls, debris fall etc.). Only one component of the motion vector is measured by DInSAR (the displacement in direction of radar illumination). Steep slopes facing the radar cannot be monitored due to fore-shortening or layover. The selection of suitable radar look direction (ascending or descending orbit) is important (ROTT, 2004). From the geotechnical point of view, these techniques have the advantage of being able to monitor extended areas and volumes and not only points as in the case of extensometer or GPS devices (MAZZANTI, 2011). Furthermore, the radar technology allows to monitor data in real time, which

is an important advance especially in rock slope monitoring). In particular, advanced multi-temporal InSAR techniques, such as Persistent Scatterer Interferometry (PSI) are able to detect and monitor, with millimetric precision, displacements occurring on selected radar targets, or Persistent Scatterers (PS) (FERRETTI *et alii*, 2001; FARINA *et alii*, 2006; BIANCHINI *et alii*, 2012; BOVENGA *et alii*, 2017), exhibiting stable radar backscattering properties.

INNOVATIVE INTEGRATION OF MONITORING TECHNIQUES

Each of the monitoring techniques above described has advantages and limitations. Generally, traditional landslide monitoring technologies permit to define the critical values of displacement and/or acceleration into landslide body, but do not allow real time warning signs to be generated. On the contrary, remote-sensing monitoring devices can be capable of inspecting an unstable slope with a high spatial and temporal frequency, but allow solely measurements of superficial displacements and deformations. The technological evolution exportable to the field of land instability monitoring is particularly lively and allows the use of warning systems unthinkable just few years ago.

Two original monitoring techniques has been tested by the Authors, in a large temporal range, in different study cases: single beam laser (SBL) and acoustic emission (AE) monitoring.

The measurement, carried out by SBL, is performed by using the technique of the difference between the emission phase and the return phase. The system is designed for measuring the distance values of natural or artificial targets at scheduled times in the range from 0.1 m to 100 m with submillimetric precision. The system (Fig. 12) is equipped with a microcomputer, which, after analyzing, stores data and transmits them through a GSM/GPRS system to the center unit, without the wiring to external network. Therefore, the scanning time or interval can be imported from a remote location, as well as data reception by means of sms or e-mail. In presence of displacements higher than the established attention or alarm thresholds, the laser system independently sends an alarm to the monitoring centre. The SBL apparatus, in the most recent configuration, can connect two wired lasers and

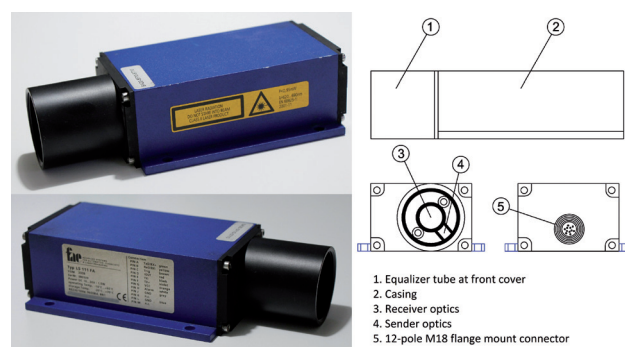


Fig. 12 - Laser Distance Meter LS1501 function elements

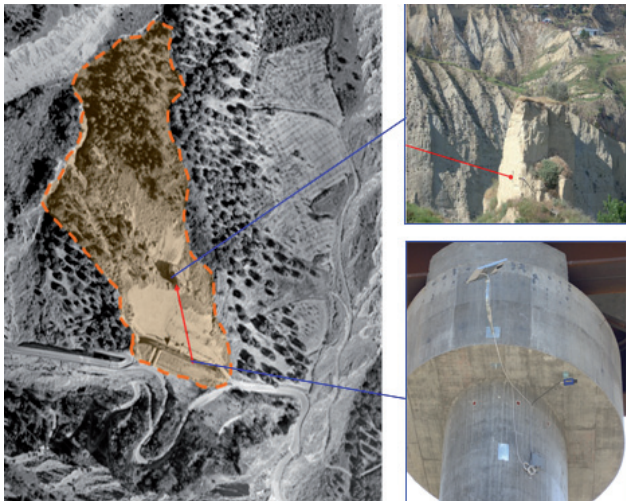


Fig. 13 - Laser monitoring system of Aliano (Basilicata, Southern Italy) landslide

up to eight wireless sensors. This configuration allows, unlike the robotic total stations, the positioning of laser device in the most appropriate locations in relation to the movement direction, thereby improving the overall performance of measurement system. Finally, the sensor with 100 m capacity is switchable with laser sensors with 500 m or 1,000 m capacities. In these

cases, however, measurement accuracy and error are proportional to the measured distance. Figures 13 and 14 show, respectively, the laser system realized for monitoring the Aliano landslide (SPILOTRO & GLISCI, 2005) and the displacements-time diagram for a sandy pinnacle located in the central body of landslide.

The fluctuation of measures is due to two types of error, environmental random error and environmental cyclic error. The main components of the error are:

- Changes in density, dust and moisture content of the air - dew on lenses surfaces - smoke.
- Parasite radiation entry from sunlight.
- Angular incidence of the reflecting surface.
- Roughness of the reflecting surface.
- Amplitude of the reflecting surface (varying with the distance).

The acoustic emission monitoring may be used to investigate the propagation of micro-cracks and formation of failure surface in slopes, especially in those made by stiff materials (AMITRANO *et alii*, 2005; GALGARO *et alii*, 2005; ROSE & HUNGR, 2007; SENFAUTE *et alii*, 2009). This kind of materials develops a brittle failure, with rapid propagation of cracks and formation of slide surface (EDELMANN *et alii*, 1994). With traditional monitoring methods, crack propagation can only be identified on the slope surface. Surface displacement can be detected too late for safe management of the monitoring of the instable masses. Since

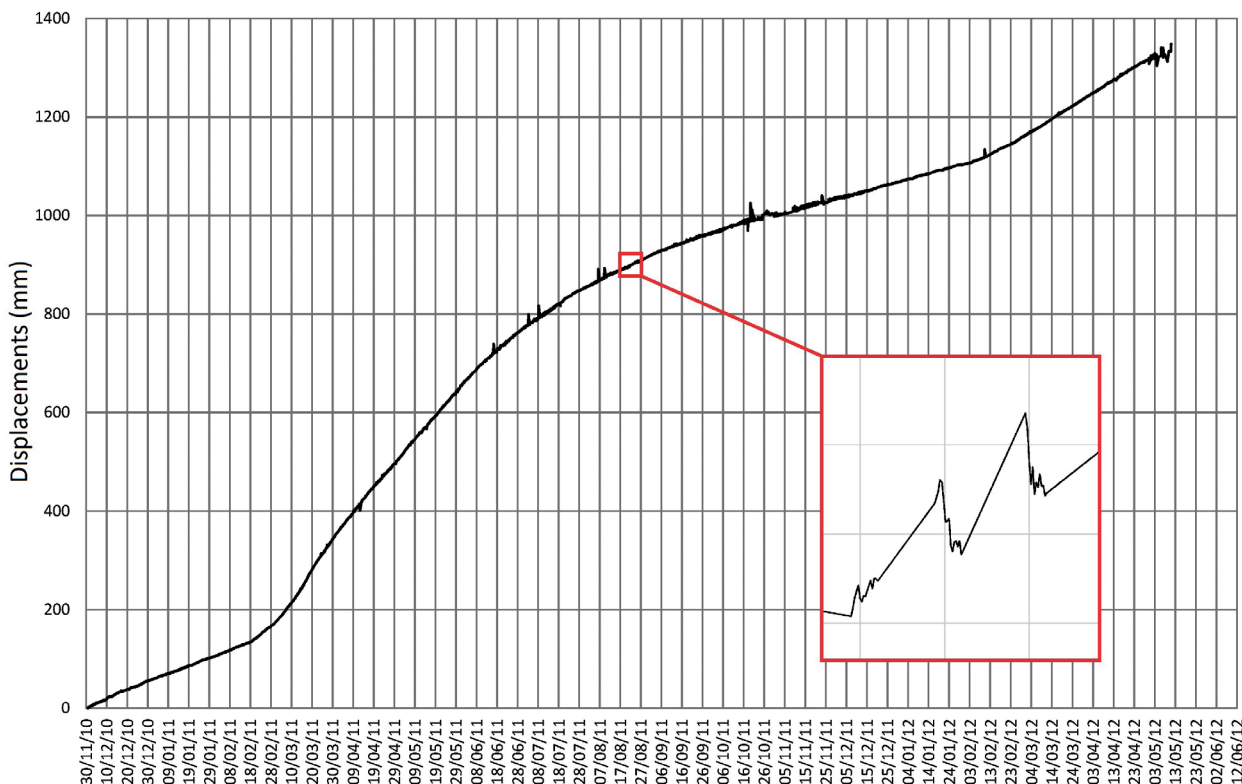


Fig. 14 - Temporal trend of the displacement of sandy pinnacle located in Aliano landslide

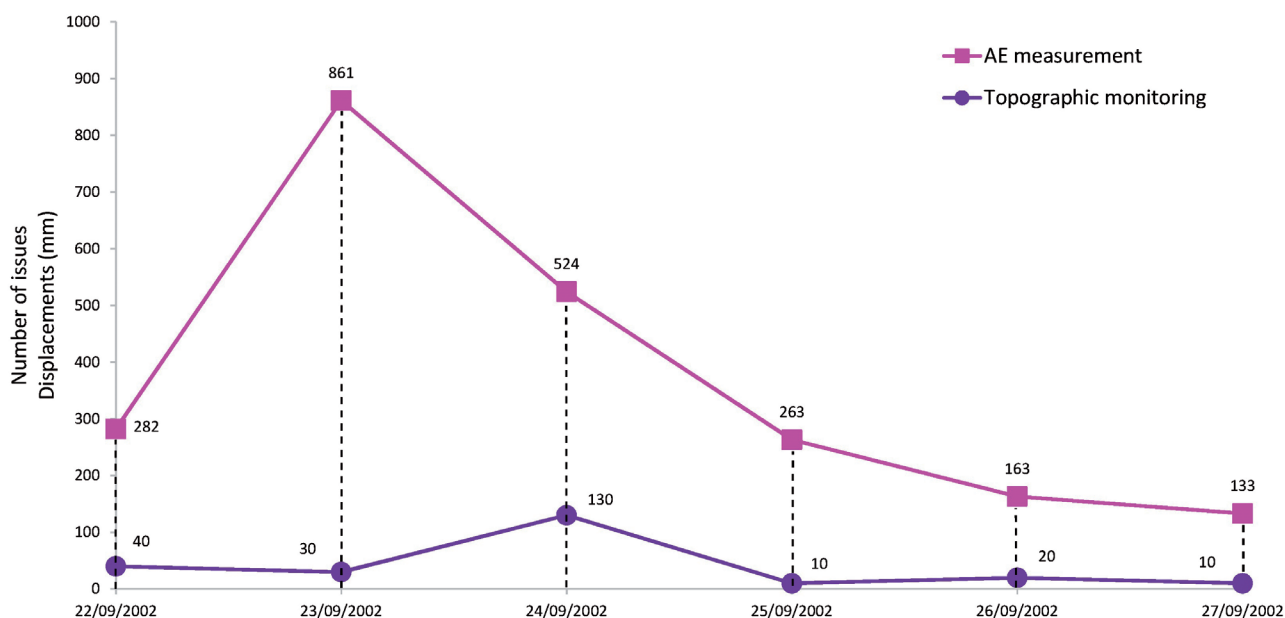


Fig. 15 - Superficial displacements of landslide related with number of issues in time

the deformations and displacements measurable on surface, by conventional monitoring devices or remote-sensing techniques, are associated with the failure of the rock mass in the post peak region, often at the residual strength level, the deformation control measures do not allow real time warning signals to be generated.

Indeed, in stiff materials the deformations are associated to micro distortions or micro failures, with release of vibrational energy in the acoustic range of the frequencies (LOCKNER, 1995; CAI *et alii*, 2007). Therefore, the survey of such precursors can result extremely profitable to the goals of an early recognition of the evolution of stress and strain states towards the progressive failure.

In general, the working scheme of AE detecting system may be of two type, with multi or single point noise detection. In the first case the recorded noises are analyzed, the event is localized in space and the noise acceptance depends on position of the event. The working scheme used by Authors is characterized by single point noise detection.

The main operations are:

- noise recording and sampling for a determinate period of time;
- signal processing by means of FFT and temporal analysis, in order to define the noise characteristic parameters, in term of frequency, intensity and time;
- parameter recording in sequential database;
- comparison with exclusion parameters and attention threshold;
- signal transmission;
- count of attention event;
- transmission of alert or alarm signals.

The monitoring of AE is currently in progress in the Aliano

landslide, constituted mainly by cementated sands, where today part of the landslide body is still moving. The acoustic emission detecting device is constituted by a geophone inserted to a depth of 11.5 meters (within cementated sands) from field surface by an extension cord. In Figure 15 are represented the results of AE monitoring in terms superficial displacements of landslide related with number of issues in time. By analyzing the number of acoustic emission events correlated to daily measurements of superficial displacements, during the landslide reactivation in August 2002, it is possible to note that the first significant acoustic activity precedes landslide movement of almost 24 hours.

CONCLUSIONS

Assessment of slope failure mechanisms requires an understanding of structural geology, geomorphology, groundwater, rock/soil mass strength and deformability conditions and seismicity. With an effective monitoring system the kinematic aspect of mass movements can be identified in the whole investigated area.

The acceleration measurements allow to evaluate the equilibrium variations. It is important to distinguish between the phenomenon analysis and the determination of reaching of decisional points. Furthermore, it is necessary to define previously a threshold and have control points in real time, which allow to discern the achievement or not of the threshold. For all measurement and monitoring procedures it is important the precision and accuracy not of measure but of the temporal variation of measure.

APPENDIX:

*Meaning of the acronyms**TDR: Time Domain Reflectometry**GPS: Global Positioning System**AIS: Automate Inclinometer System**IDMS: Image Detection Monitoring System**TLS: Terrestrial Laser Scanners**LiDAR: Light Detection And Ranging**SAR: Synthetic Aperture Radar**PSI: Persistent Scatterer Interferometry**InSAR: Interferometric Synthetic Aperture Radar**DInSAR: Differential Interferometric Synthetic Aperture Radar**SBL: Single Beam Laser**AE: Acoustic Emission***REFERENCES**

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Received May 2016 - Accepted January 2017

