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Paolo Mazzanti
University of Rome "Sapienza", Italy

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INVESTIGATING THE BEHAVIOUR OF NATURAL SLOPES AND MAN MADE STRUCTURES BY TERRESTRIAL SAR INTERFEROMETRY

Paolo Mazzanti
Department of Earth Sciences, University of Rome "Sapienza", Rome, Italy
NHAZCA S.r.l. spin off University of Rome "Sapienza", Rome, Italy

ABSTRACT

Remote sensing techniques for the monitoring of deformation are opening new opportunities in the field of geotechnical engineering and geology. Terrestrial SAR interferometry (TInSAR) is one of the most innovative technique and it promises to be a very effective solution which will be extensively used in the near future. TInSAR is characterized by several interesting features such as: i) high density of information; ii) fully remote capability; iii) long range capability; iv) widespread view; v) spatially continuous efficacy and vi) high accuracy. Thanks to these features TInSAR has been used for investigation and diagnostic purposes (i.e. landslide and structural instability mapping, state of activity evaluation, analysis of triggering factors and modelling of deformational behavior) thus providing very useful results.

INTRODUCTION

Over the last decades, the monitoring of deformation has become an important and widely accepted tool for the control of stability conditions of geological, geotechnical and structural problems. Hence, a plan for the monitoring of deformation is nowadays required on several contexts related to large construction projects (tunnels, dams, highways, only to mention the most common). In other words, the deformation is considered one of the most effective information to understand the behaviour of ground/structures we are interacting with and, therefore, the monitoring of deformation is seen as a useful solution.

The monitoring of deformation during large construction projects (i.e. the observation method) is now widely accepted and, quite often, is also imposed by authorities in charge of workers safety and by insurance companies.

Instead of the extensive use of the deformation monitoring, it is difficult to found international scientific schools dedicated to this topic. A comprehensive discussion about this matter is well beyond the purpose of this paper, however, it is worth to note that this lack may lead to difficulties in determine a strong philosophy of the deformation monitoring. Furthermore, also the innovation process in this specific field is negatively affected. As a matter of fact, instead of the increasing number of new technical solutions which have been developed on the last years, their introduction to construction projects is quite slow and, when it happens, their capabilities are quite often downgraded to fit a "traditional" view. Moreover, the rapid development of remote methods for the monitoring of deformations observed on the last years has furtherly complicated the scenario, thus introducing a new monitoring approach that is quite different from the traditional one based on contact instruments.

The main purpose of this paper is to suggest a new philosophy of deformation monitoring that, in the author's idea, is the natural consequence of the new opportunities offered by remote methods (Mazzanti, 2012).

By showing some real examples based on the application of the Terrestrial SAR Interferometry we will try to make the reader conscious that the monitoring of deformation can be not both a control tool and an investigation and diagnostic toll.

In other words, under certain conditions, the monitoring of deformation allows to derive information on the behavior of both natural and man made structures that may be useful for both decision making and design purposes.

REMOTE METHODS FOR THE MONITORING OF DEFORMATION

Remote methods are changing the traditional view of deformation monitoring mainly due to the following reasons (Mazzanti, 2012):

1) they are characterized by a “far view”, this means that they have the opportunity the look with a wider perspective than contact systems, even if, quite often, they are less precise in term of positioning;
2) their use is negatively affected by the presence of obstacles along the line of sight (vegetation, working machines etc);
3) they do not require the direct interaction with the monitored object/area;
4) they may only look at the superficial effect of the ground/structure deformation;
5) their accuracy is strongly site-specific (depending on distances, weather conditions etc);
6) in some cases they are able to derive information about historical displacements.

These features imply both advantages and limitations with respect to contact monitoring systems, but it is not the intention of the author to discuss about this point. For the aim of this paper it is enough to outline that several differences exist and that they may lead to different rick and opportunities.

Available technical solutions

Remote sensing methods may be classified in two main categories, i.e. partially remote techniques and fully remote techniques (Mazzanti 2012). Only the second category is characterized by all the features described above and, especially, by the fully contactless approach, since they do not require the installation of targets or sensors on the ground/structure.

Among these techniques the followings are the most common and they can be applied by different platforms (ground, aerial and satellite):

i) Laser Scanning (Heritage and Large, 2009);
ii) Digital Photogrammetry and Image Correlation (Kasser and Egels, 2002);
iii) SAR Interferometry (Bamler & Hartl, 1998).

These techniques are based on different physical principles and they use different wavelengths, but they share some key features such as: i) the widespread view, ii) the fully remote efficacy.

Two of them (aerial photogrammetry and satellite InSAR) allow also the monitoring of historical deformation thanks to the availability of past images collected by national and international agencies. For example, for satellite InSAR, images are available, in dedicated archives, from 1992. Hence, monitoring of displacements occurred on the last 20 years are theoretically feasible.

A comprehensive review of the main technical features, advantages and limitations and main fields of application of remote methods for deformation can be found in the paper by Mazzanti, 2012.

In this paper we focus only on Terrestrial SAR Interferometry, a technique developed at the end of 90’, that in the author’s opinion, represents one of the most interesting and innovative frontiers in the field of remote monitoring of deformations.

Terrestrial SAR Interferometry

Terrestrial Synthetic Aperture Radar Interferometry (TInSAR, also referred as GBInSAR) is a ground based Radar technique for the remote monitoring of displacements (Antonello et al, 2004; Luzzi 2010; Mazzanti 2011). TinSAR is applied by using an equipment made of a linear rail and a radar sensor (Fig.1). By the movement of the sensor along the rail, 2D SAR images are derived. Then, by the interferometric technique (i.e. by comparing the phase difference of each pixel between two or more images collected at different times) the displacements along the instrument line of sight (LOS) are derived. Hence, both colored images and time series of displacement of each pixel can be achieved (Fig.2). Pixel resolution ranges from less than one meter to few meters depending on the rail length and the sensing distance. The accuracy in the displacement measurement may range from few decimal mm under ideal conditions (short term and short distance monitoring), to some mm in more complex conditions.

Fig. 1. Picture of the TInSAR system IBIS-L by IDS S.p.A. installed on a QUIB basement by NHAZCA S.r.l..

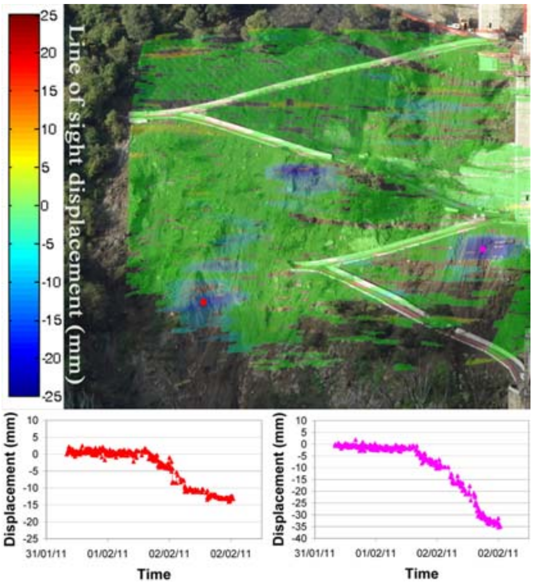

Fig. 2. Displacement map overlaid to a slope picture and time series of displacement of two pixels.

Depending on the used equipment the temporal resolution (i.e. the data sampling rate) of SAR images may range from few minutes to few seconds. Furthermore, by using microwaves signals TInSAR is able to collect data under any weather and lighting conditions.

TInSAR monitoring can be performed by installing the equipment in a stable location with a panoramic view (up to 4 km far from the monitored area), and it does not require the installation of contact sensors or reflectors in the monitored area.

THE MONITORING OF DEFORMATION FOR INVESTIGATION AND DIAGNOSTIC PURPOSES

Investigation and diagnosis of geological, geotechnical and structural problems can be performed by several approaches and methods. The most traditional and used approach is the visual inspection by experts that are able to identify useful features on the basis of their experience. For example, when dealing with a slope instability the observation by a geomorphologist is the first approach. As a matter of fact, by looking at the geomorphological features of the slope it is possible to "hypothesize" the boundary of a landslide, its classification, the expected depth etc. The same can be said for a man made structure like a bridge; by looking at the color and aspect of the concrete, the presence of humidity, cracks and other features a structural engineer is able to derive some basic information about the bridge status.

However, several investigating techniques are available in case the visual inspection is not enough. This tolls are able to investigate both the surface and the inner features of the ground/structure. Available techniques can be classified in direct and indirect ones. Regarding the first category the following methods are listed: borehole, penetration tests, measurement of temperature, measurement of the water presence etc. On the other hand, the term indirect methods is quite often associated to geophysical techniques, e.g. active and passive seismic, electrical tomography, ground penetrating radar etc. These methods are extensively used in the diagnosis and investigation of both natural terrain and man made structures.

The investigation approach is commonly used in different phases of a project dealing with geological or geotechnical matters, from the preliminary analysis, to the design phase, up to the management and maintenance phases.

Differently, system for the deformation measurement are commonly used only as a control system on the management phase and sometimes on the maintenance phase.

In this paper is argued that the monitoring of deformation can be an effective solution for investigation and diagnosis, especially if carried out by innovative techniques that are able to collect a huge amount of information.

It is a matter of fact, that the deformation is one of the most common effects of geotechnical problems and therefore the presence of an active deformation is a clear indicator of an actual problem. For example, in the case of a landslide whose boundaries have been derived by visual inspection, several additional information can be gained by the measurement of deformation. By monitoring the movement it is possible to detect the active area inside the "visually derived" boundary or to identify the precise depth. In other words, in the author's opinion, the movement/deformation is an indicator as effective as other parameters (geological cross section, geophysical features etc) for the investigation of a landslide. Furthermore, it is worth to note that the deformation is more objective than other parameters, since it is less influenced by the interpretation of the operator.

At this regard, Terrestrial SAR Interferometry is a very powerful investigation technique, mainly thanks to the high information density and the high accuracy in the displacement measurement. Furthermore, with respect to the traditional diagnostic equipments, it is characterized by the great advantage of collecting information by a remote position (particularly useful when the direct access to the site is difficult or dangerous).

In what follows several examples of investigation of geotechnical problems by the support of Terrestrial SAR Interferometry monitoring are presented with a particular focus to slope instabilities.

INVESTIGATION BY TERRESTRIAL SAR INTERFEROMETRY

Over the last 9 years the author has followed the development of the TInSAR technique from its early stage, by using the first developed prototypes, to extensive and long term applications by using industrial equipments. This long term experience allowed to investigate and to experience the main advantages and limitations of TInSAR and its efficacy on different contexts. Specifically, the author has been directly involved in projects concerning volcanoes, architectural heritages, civil buildings, dams, bridges, viaducts, tunnels, pipelines and several slope instability processes ranging from earth-flows, deep seated rotational landslides, small translation landslides up to rock cliffs instabilities (Bozzano et al, 2008, 2009, 2010, 2011, 2013; Mazzanti and Brunetti 2010; Mazzanti et al, 2011a-b; Mazzanti and Cipriani 2011; Prestininzi et al, 2012).

In the early stage TInSAR technique has been appreciated and applied mainly as an efficient and safe solution for the continuous control of instability processes which may generate risk to the man and its activities (Casagli et al, 2003; Casagli et al, 2010; Bozzano et al, 2011). For this application the following main features have been looked for: i) fully remote capability; ii) accuracy in displacement measurement; iii) high sampling rate; iv) effectiveness under each weather and lighting conditions.

In recent years TInSAR has demonstrated to be a powerful weapon in the hands of geologists and geotechnical and structural engineers to investigate ground and structural instability processes thanks to the same features described above, but also thanks to: i) the "panoramic view" capability; ii) the spatial continuous information; iii) the high information density and sensing distance.

In what follows some examples of TInSAR monitoring for investigation purposes are described.

Landslides

Landslides are probably the geological/geotechnical process more analyzed by Terrestrial SAR Interferometry (Antonello 2004; Luzi, 2010; Mazzanti 2011 and references therein).

The first case is the TInSAR monitoring of an unstable slope overlooking an artificial lake in a mountainous region (up to 3000 m above sea level). Such a large slope shows peculiar geomorphological features that may suggest potential large and deep seated instability processes that could lead to dangerous effects to a large man made infrastructure located downslope. Due to the altitude (from 2000 to 3300 m above the sea level) and the morphological features, only the lower part of the slope can be properly investigated by common surveying techniques and monitored by traditional deformation monitoring techniques. Hence, detailed data about slope instability processes acting on the lower part of the slope are available, but no information can be derived on the upper part of the slope. Since 2010 three continuous monitoring surveys by TInSAR, up to three months long, have been performed, during the summer season (when the slope where not covered by the snow), thus trying to collect useful information about the behavior of the upper part of the slope. Collected data allowed to achieve long term displacement maps of the overall slope and accurate time series of displacement. Localized areas, up to few square hundreds meters large, affected by displacement up to 2 mm/days were detected in the upper part of the mountain (Fig.3). These areas, correspond to talus deposits, therefore, their movements have been interpreted as the result of surface processes generated to an inclination of the debris close to the stability angle. The constant rate displacement during the monitoring time furtherly confirmed the talus process. No other movements were detected on the slope, neither in the upper and in the lower part (where data were confirmed also by traditional sensors), thus suggestion an overall stability condition of the slope.

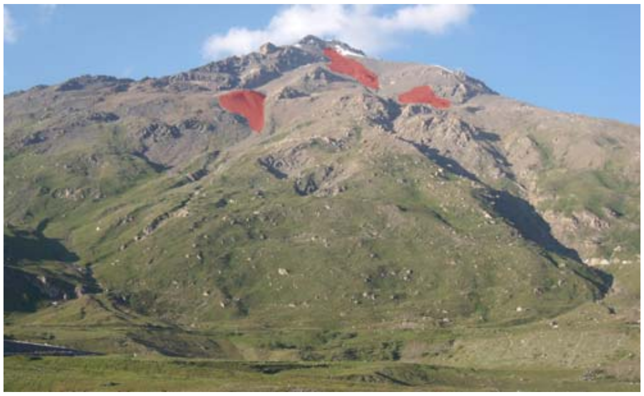

Fig. 3. Picture of the slope and identification (in red) of the three zones affected by displacements.

In 2009 one year continuous monitoring of a slope affected by an earth flow, located in the Lazio Region (Italy), were carried out mainly for emergency issues (Bozzano et al, 2009). A small amount of the slope, failed in the late 2008 following an intense rainfall. Due to the geological nature of the involved material, made of alluvial sandy and silt deposits of the Tiber river, and to the high percentage of water, the failed material propagated in the lower part of the slope as an earth flow, thus hitting some houses and a major pipeline (Fig.4).

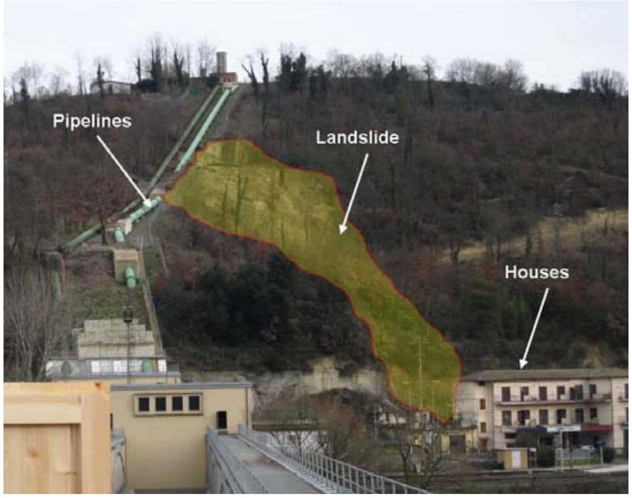

Fig. 4. Picture of the slope and identification of the 2008 earth flow (in yellow) and affected houses and pipelines.

Due to the unstable conditions of the area and to the dynamic of the landslide, conventional investigation methods (geological surveys, geophysics, borehole etc) were not feasible, therefore only a visual inspection could be performed.

The continuous monitoring by TInSAR, with a sampling rate of around 5 minutes, allowed to gain several information about the behaviour of the slope. Displacements collected on the first day showed movements up to 40 mm along the LOS (Line Of Sight) in the deposit zone, while no movements were detected in the source area of the slope (Fig.5). Hence, hazard were mainly related to the flowing deposit, and no imminent retrogressive processes were going on.

Data collected during the following days confirmed the stability of the up slope scarp and the movement of the debris. Regarding the deposit, it was possible to depict a displacement behavior characterized by heterogeneous movements with accelerations and decelerations localized to small areas and a rapid response (i.e acceleration) to rainfalls. Such a behaviour was interpreted as the result of a superficial movement of the mass, which implies a low hazard to infrastructures.

A similar application was carried out in an unstable slope characterized by a basal surface up to 30 m deep located in the Northern part of Italy (Fig.6). Two TInSAR monitoring surveys, 4 days long, were carried out in 2011 in order to collect additional information about the slope behaviour. As a matter of fact, several point based geological and geotechnical data were available as well as punctual surface and deep displacement behaviour derived from GPS and inclinometer measurements. However, spatially continuous information about the slope behaviour were not available and, still more, the lower part of the slope were not suitably controlled due to its steepness and high erosion rate. Data collected in the frame of the two short term TInSAR surveys were enough to map the area affected by movements with respect to the stable one. Achieved results showed an homogeneous movement of the overall slope on the order of 1 mm/day and localized portions in the lower part of the slope affected by higher movement rates (up to 4-5 mm/day). These higher movements were mainly localized in an impluvium, hence they provide information about the erosive attitude of this specific zones.

It is worth to note that TInSAR data confirmed the landslide boundary depicted by traditional surveys and deformation monitoring, but it allowed to refine them thanks to the spatially continuous information.

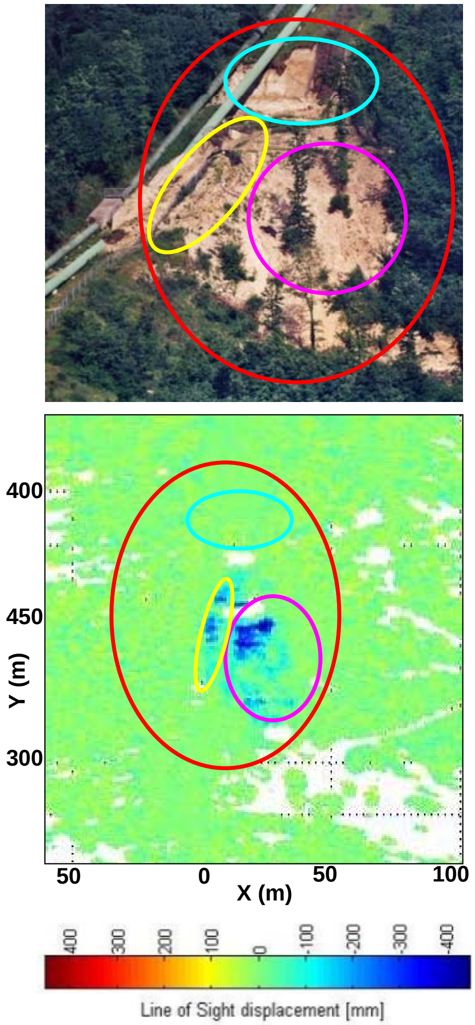

Fig. 5. Picture of the landslide (in the upper part) and 24 hours displacement map of 23-01-2009 (in the lower part). Colored ellipses identify corresponding sectors.

Fig. 6. Perspective view of the TInSAR interferometer IBIS-L and slope overlaid by the displacement map.

In the author's experience, the most interesting application of TInSAR is the monitoring of a complex deep seated landslide affecting the entrance of an under construction tunnel in the southern part of Italy (Bozzano et al, 2008, Bozzano et al, 2011; Bozzano et al, 2012 this volume). Following the collapse of the tunnel entrance, occurred during its construction, a detailed investigation of the slope were carried out (Bozzano et al, 2011), thus allowing to achieve an engineering geology model of the slope and to design countermeasures for its stabilization. The continuous monitoring by TInSAR allowed to detect different displacement patterns of the slope and its reaction with stabilization structures (anchored bulkheads, gabions, spritz beton etc) during different phases such as excavation, realization of structures and tunneling (Bozzano et al, 2011; Bozzano et al, this volume). Furthermore, by the combination of TInSAR data with other collected information, a detailed zoning of the whole slope was done. However, the most contribution of the TInSAR monitoring were the comprehension of the overall dynamics of the slope and its reaction to rainfalls and excavation activities. Specifically, by the back analysis of more than 10 landslides (from 10 to 10.000 m^3), occurred during the monitoring time, the main behaviour of slope before failure were derived (Mazzanti et al, 2011). Suitable models for the prediction of landslides where also developed and calibrated (Bozzano et al, 2012), thus allowing the prediction of future events and the displacement to rainfall correlation to be derived. A similar investigation has been performed also for the anchored bulkheads, thus allowing an improved definition of stability thresholds with respect to the one derived from geotechnical data (Bozzano et al, 2012).

Rock cliffs

Gravity driven instabilities from rock cliffs are probably one of the most common processes occurring in mountain regions (Dorren, 2003). Even if they rarely involve large volumes of rock, nevertheless, they may cause several problems to human activities. Since they usually origin from vertical and unstable cliffs their investigation is quite complex and few suitable instrumentations are available. Over the last years some authors are trying to apply remote sensing methods for the investigation of natural and man made rock cliffs (among the others Lim et al, 2005; Oppikofer et al, 2009; Mazzanti et al, 2011). At this regard, recent studies have demonstrated that TInSAR may represent a useful tool to investigate the stability condition of natural cliffs (Mazzanti & Brunetti, 2010) and that it is still more effective if combined with other remote and traditional techniques (Mazzanti et al, 2011).

By monitoring vertical cliffs it is possible to identify sectors affected by permanent micro-movements (sometimes half a mm or still less) which may indicate a fairly stable condition. Furthermore, by comparing TInSAR time series with temperature and rainfalls data it is possible to identify blocks affected by cyclic movements which can be then assumed as the most susceptible to collapse (Mazzanti and Brunetti 2010). These information may be very useful if combined with standard investigation systems based on geomechanical analysis. As a matter of fact, conventional geomechanical methods look only to preconditioning factors like joint features (orientation, spacing, aperture etc), rock stiffness etc. On the other hand, information derived by TInSAR may provide useful indicators of the state of activity of a block by looking to its deformational behaviour. Successful applications have been carried out by the author on different cases in Italy over the last years (Mazzanti and Brunetti, 2010; Mazzanti et al, 2011).

Man-made structures

Remote monitoring of deformation of man-made structures by TInSAR may be very useful to complement conventional solutions. In what follows two examples are briefly presented.

The precise mapping of sectors of a building affected by displacement may be derived from TInSAR monitoring thanks to its widespread view and spatially continuous capability. An interesting example refers to a civil building in the city or Rome which was affected by displacements during the underground activities for the realization of the third Metro Line in Rome (Mazzanti and Cipriani, 2011).

The rapid mapping of the deformation pattern of a concrete or earth dam in response to increasing and decreasing of the water level may be easily derived by TInSAR monitoring. Also in this case the following features are particularly relevant: i) widespread view, ii) spatial continuity of information and iii) high data sampling rate. Furthermore, especially in the case of concrete dams with a sensing distance lower than 100 m, high accuracy (on the order of 0.1 mm) in the displacement measurement can be achieved.

The identification of pressure acting on gabions and retaining walls may be also derived by the continuous displacement measurement by TInSAR (Bozzano et al, 2011; Bozzano et al, this volume).

CONCLUDING REMARKS

Some decades ago Prof. Ralph Peck was conscious that "*The observational method, is one of the most powerful weapons in our arsenal…*", and therefore he suggested that "*We need to carry out a vast amount of observational work, but what we do should be done for a purpose and done well" (R. Peck).* In this paper several case histories where the observation method was successful applied are presented. The focus has been placed on an unconventional "*purpose*", i.e. the investigation and diagnosis of geological, geotechnical and structural instability problems. As a matter of fact, after Peck time, several new techniques have been developed in the field of deformation monitoring, thus increasing the opportunities offered by the observational approach, like the investigation purpose. Terrestrial SAR Interferometry (TInSAR) is probably one of the most interesting, among these techniques, since it combines several useful features like: i) fully remote efficacy; ii) widespread view; iii) spatially continuous information (i.e. maps of displacement instead of single points); iv) long range attitude (up to some km); v) effectiveness under any lighting and weather conditions and vi) high accuracy in displacement measurement.

The huge amount of information provided by TInSAR, has been demonstrated to be very effective for investigation purposes. Several information can be gained on a geological, geotechnical or structural conditions by a suitable monitoring of deformation by TInSAR such as: i) precise mapping of active slope and structural instabilities; ii) identification of stable vs unstable zones (i.e. moving and not moving zones); iii) analysis of displacement correlation with triggering factors (e.g. rainfalls, excavations etc). All these data, if suitably combined with already available information, may allow also to calibrate models describing the behaviour of slopes or structures.

However, it must be pointed out that other remote methods of deformation like Terrestrial Laser Scanning and Satellite SAR Interferometry shares these "investigation capabilities" with TInSAR.

To conclude, thanks to the recent developments and available techniques, the monitoring of deformation is now a new weapon for geologists and engineers in the investigation of their professional challanges.

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