Monitoring Natural Slopes and Man-made Structures by TInSAR: Understanding Behavior and Forecasting Method

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ABSTRACT

Remote sensing techniques for the monitoring of displacements are opening new opportunities in the field of geotechnical engineering and geology. Terrestrial SAR interferometry (TInSAR) is one of the most innovative techniques 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) panoramic perspective; (v) spatially continuous efficacy and (vi) high accuracy. Thanks to these features, TInSAR has been used for investigation and diagnostic purposes (viz. landslide and structural movement monitoring,), and provided very useful data.

1 INTRODUCTION

Over the past decades, displacement/movement monitoring has become an important tool for assessment of stability conditions for the control of many geological, geotechnical and structural problems. Hence, it is now a common requirement to have various monitoring plans covering different aspects in large construction/infrastructure projects (e.g. tunnels, dams, highways). In other words, displacement data obtained through monitoring is considered one of the most useful information for understanding the behavior of the ground/structures that we are interacting with and, therefore. Monitoring of displacements is in fact now widely accepted and, quite often, is also imposed by authorities in charge of workers safety and by insurance companies.

By showing some real examples based on application of Terrestrial SAR Interferometry we aim to promote better appreciation of the use of displacement monitoring as a control tool and as an investigation and diagnostic tool. In other words, under certain conditions, the monitoring of displacement 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.

2 REMOTE METHODS FOR THE MONITORING OF DISPLACEMENTS

Recent development in methods of remote monitoring are changing the traditional view for the following reasons (Mazzanti 2012):

1) they are characterized by a "panoramic perspective", this means that they provide the opportunity for looking at the subject area 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 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 (e.g. satellite InSAR) 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 authors to discuss about this point. For the aim of this paper it is enough to outline the differences and the different risks and opportunities that may have led to.
Remote sensing methods may be classified in two main categories, viz. (1) partially remote techniques and (2) 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.

2.1 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 equipment made of a linear rail and a radar sensor (Fig.1). The sensor, moving along the rail during data acquisition, derives 2D SAR images. Then, by the interferometric technique (i.e. by comparing the phase difference of each pixel between two or more images collected at different times) 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 displacement measurement may range from few decimal mm under ideal conditions (short term and short distance monitoring), to some mm in more complex conditions.

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

Depending on the equipment used, the temporal resolution (i.e. the data sampling rate) of SAR images may range from a few minutes to a 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 (up to 4 km away) with a panoramic view of the monitored area, and it does not require the installation of contact sensors or reflectors in the monitored area.

3 INVESTIGATION BY TERRESTRIAL SAR INTERFEROMETRY

Over the past 9 years the authors have been following the development of the TInSAR technique from its early stage, viz. the trial use of the first developed prototypes, to extensive and long-term applications by using industrial equipments. This long-term involvement allows the authors to build up experience in its use and to understand its main advantages and limitations of TInSAR and its efficacy in different applications. Specifically, the authors have 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 and rock cliffs instabilities (Bozzano et al, 2008, 2010, 2011; Mazzanti et al, 2011a; Mazzanti & Cipriani 2011).

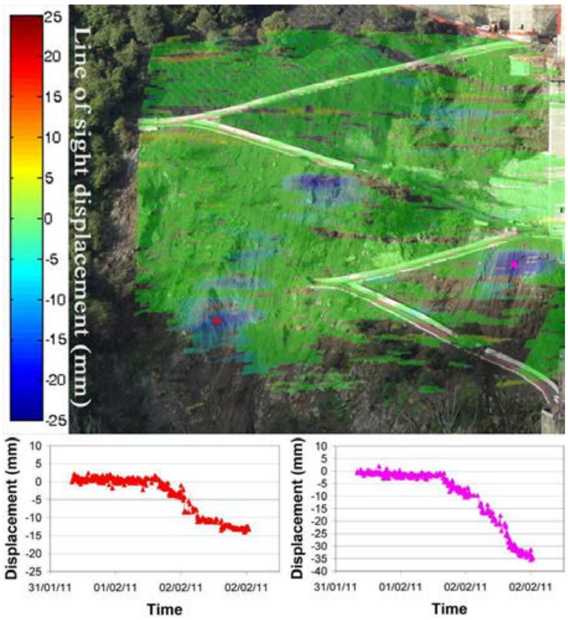

Figure 2. Displacement map overlaid to a slope picture and time series of displacement of two pixels.

In the early stage development of TInSAR technique, it was used mainly as an efficient safety control measures for continuous monitoring of instability processes which may generate risk to life and human activities (Casagli et al, 2003; Casagli et al, 2010; Bozzano et al, 2011). For this application the following main features are required: (i) fully remote capability; (ii) accuracy in displacement measurement; (iii) high sampling rate; (iv) effectiveness under all weather and lighting conditions.

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

Selected case examples of TInSAR monitoring for investigation purposes are described below.

3.1 Landslides

Landslides are probably the geological/geotechnical process that analyzed most extensively using Terrestrial SAR Interferometry (e.g. Antonello 2004 et al; Luzi 2010; and Mazzanti 2011b).

In 2009, a slope affected by an earth flow, in the Lazio Region (Italy), was monitored continuously for one year mainly as an emergency measures. A small portion of the slope, failed in the late 2008 following an intense rainfall. Due to the geological nature of the materials involved, e.g. alluvial sand and silt deposits of the River Tiber, and due to heavy water ingress, the landslide debris at the lower part of the slope moved forward as an earth flow, hitting some houses and a major pipeline (Fig.3).

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, and only a visual inspection could be performed.

The continuous monitoring using TInSAR, with a sampling rate of around 5 minutes, provided useful information on the slope behavior. Displacements collected on first day showed movements up to 40 mm along the 'Line of Sight' (LOS) in the deposit zone, while no movements were detected in the source area of the slope (Fig.4). Hence, the hazards were found to be mainly related to the flowing deposit, and no imminent retrogressive processes were going on.

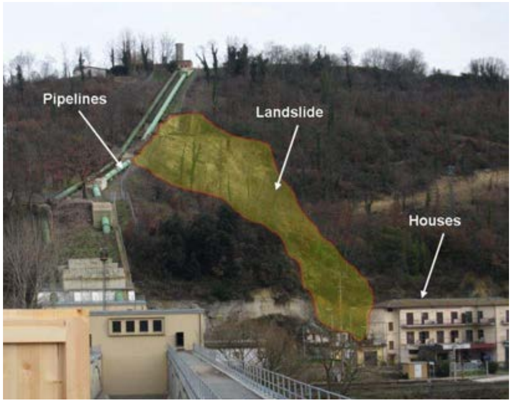

Figure 3. Picture of the slope and identification of the 2008 earth flow (in yellow) and affected houses and pipelines.

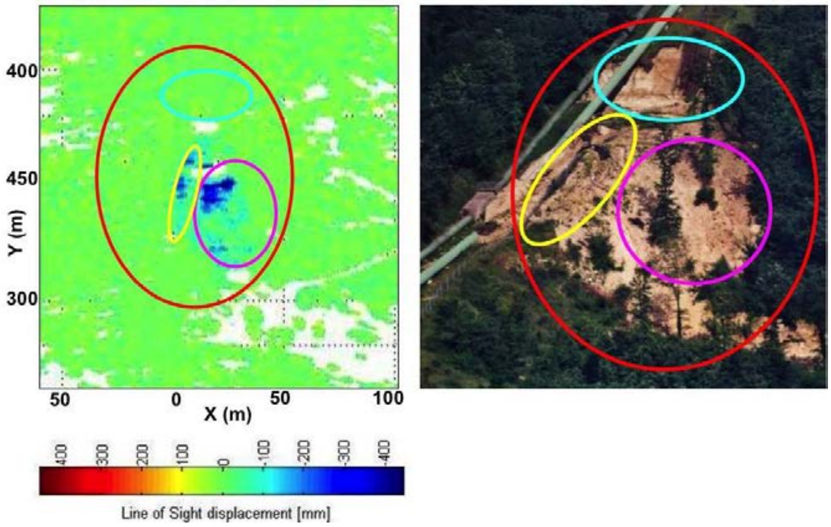

Figure 4. Picture of the landslide (on the right) and 24 hours displacement map of 23-01-2009 (on the left). Colored ellipses identify corresponding sectors.

Data collected during following days confirmed the stability of the up slope scarp and the movement of 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 behavior was interpreted as the result of a superficial movement of the mass, which implies a low hazard to infrastructures.

In the authors'experience, one of the most interesting applications of TInSAR is the monitoring of a complex deep-seated landslide affecting the entrance of a tunnel during construction in the southern part of Italy (Bozzano et al, 2008, Bozzano et al, 2011; Bozzano et al, 2012). Following the collapse of the tunnel portal during 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 detection of different displacement patterns of the slope and its reaction with the stabilization measures implemented (viz. anchored bulkheads, gabions, shotcrete, etc.) during different phases such as excavation, construction of the structures and tunneling (Bozzano et al, 2011). Furthermore, by the combination of TInSAR data with other collected information, a detailed zoning of the whole slope was undertaken. However, the main contribution of TInSAR monitoring was the understanding of the overall transient behavior 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 m3), occurred during the monitoring time, the main behavior of the slope, before failure, was derived (Mazzanti et al, 2011b). Suitable models for the prediction of landslides were 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).

3.2 Rock cliffs

Over the past years, some authors have been trying to apply remote sensing methods for the investigation of natural rock cliffs and man-made rock cut slopes (among the others Lim et al, 2005; Mazzanti et al, 2011a). At this regard, recent studies have demonstrated that TInSAR may represent a useful tool to investigate stability condition of natural cliffs and that it is still more effective if combined with other remote and traditional techniques (Mazzanti et al, 2011a).

By monitoring vertical cliffs it is possible to identify sectors affected by permanent micro-movements (sometimes half a millimeter or 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 assumed as the most susceptible to collapse.

This information may be very useful if combined with conventional 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 behavior. Successful applications have been carried out by the authors on different cases in Italy over the past years (Mazzanti et al, 2011b).

3.3 Man-made structures

Remote monitoring of displacement 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 coverage and spatially continuous capability. An interesting example refers to a civil building in the city of Rome, which was affected by displacements during the underground activities for the construction of the third Metro Line in Rome (Fig. 5) (Mazzanti & Cipriani, 2011).

The rapid mapping of 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.

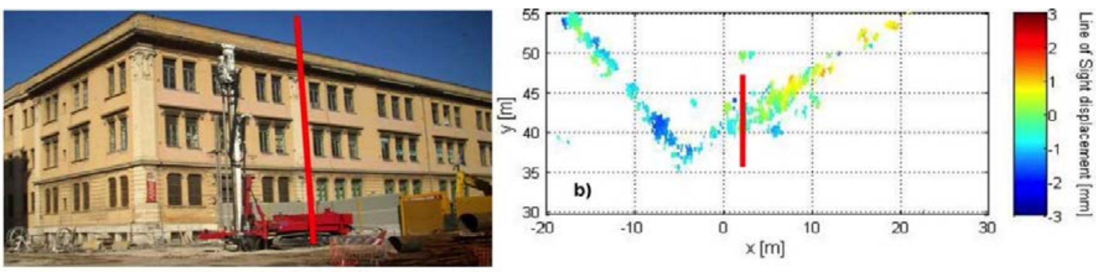

Figure 5. Picture of the building and displacements map derived by TInSAR. The red line identifies the same sector.

4 CONCLUSIONS

In this paper several case histories where the observational method was successful applied are presented. The focus has been placed on unconventional applications, i.e. the investigation and diagnosis of geological, geotechnical and structural instability problems. In the past years, several new techniques have been developed in the field of displacement 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 one 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. Various types of information can be gained, e.g. geological, geotechnical or structural conditions using suitable monitoring 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 existing information, may help to calibrate different models for describing the behavior of slopes or structures.

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

REFERENCES

Antonello, G., Casagli, N., Farina, P., Leva, D., Nico, G., Sieber, A.J. & Tarchi, D. 2004. Ground- based SAR interferometry for monitoring mass movements. *Landslides*, 1: 21–28.

Bamler, R. & Hartl, P. 1998. Synthetic aperture radar interferometry. *Inverse Problems*, 14:1-54.

Bozzano, F., Cipriani, I. & Mazzanti, P. 2012. Assessing of failure prediction methods for slope affected by human activities. In Eberhardt et al., Ed. (Taylor & Francis Group), *Landslides and Engineered Slopes: Protecting Society through Improved Understanding*: 1465-1471.

Bozzano, F., Cipriani, I., Mazzanti, P. & Prestininzi, A. 2011. Displacement patterns of a landslide affected by human activities: insights from ground-based InSAR monitoring. *Natural Hazards*, 59(3): 1377-1396.

Bozzano, F., Mazzanti, P., & Prestininzi, A. 2008. A radar platform for continuous monitoring of a landslide interacting with an under-construction infrastructure. *Italian Journal of Engineering Geology and Environment*, 2: 35-50.

Bozzano, F., Mazzanti, P., Prestininzi, A. & Scarascia Mugnozza, G. 2010. Research and development of advanced technologies for landslide hazard analysis in Italy. *Landslides*, 7(3): 381-385.

Casagli, N., Farina, P., Leva, D. & Tarchi, D. 2003. Application of ground-based radar interferometry to monitor an active rockslide and implications for emergency management. In Hermanss, R., Evans, S., Scarascia Mugnozza, G., Strom, A. Ed. (Kluwer) *Massive Rock Slope Failure* - NATO Science Series Book.

Casagli, N., Catani, F., Del Ventisette, C. & Luzi, G. 2010. Monitoring, prediction and early warning using ground-based radar interferometry. *Landslides*, 7(3): 291-301.

Lim, M., Petley, D.N., Rosser, N.J., Allison, R.J., Long, A.J. & Pybus, D. 2005. Combined Digital Photogrammetry and Time-of-Flight Laser Scanning for Monitoring Cliff Evolution. *The Photogrammetric Record,* 20: 109-129.

Luzi, G. 2010. Ground based SAR interferometry: a novel tool for Geoscience. *Geoscience and Remote Sensing New Achievements:* 508.

Mazzanti P., Bretschneider, A. & Brunetti, A. 2011a. Geomechanical investigation of coastal cliffs by terrestrial remote sensing techniques. In Gattermann, J. & Bruns, B. Ed. *Proceeding of the FMGM 2011 Conference, Berlin, Germany, 12-16 September 2011*, TU Braunschweig, ISBN: 3927610879 (In Press).

Mazzanti, P. 2011. Displacement Monitoring by Terrestrial SAR Interferometry for Geotechnical Purposes. *Geotechnical News*, June. 25-28.

Mazzanti, P. & Cipriani, I. 2011. Monitoring of a building in the city of Rome by Terrestrial SAR Interferometry. In Ouwehand, L. Ed. *Proceedings of Fringe 2011 workshop, ESA-ESRIN, Frascati. 19-23 September 2011.* ISBN: 9789290922612.

Mazzanti, P., F. Bozzano, I. Cipriani and F. Esposito 2011b. "Temporal prediction of landslide failure by continuous TInSAR monitoring". In. *Proceeding of the FMGM 2011 Conference, Berlin, Germany, 12-16 September 2011,* (J. Gattermann and B. Bruns ed.), TU Braunschweig, ISBN: 3927610879 (In Press).

Mazzanti P., 2012. Remote monitoring of deformation. An overview of the seven methods described in previous GINs. *Geotechnical Instrumentation News,* December 2012: 24-29.

Applications of Geotechnical Baseline on Deep Excavation and Foundation

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ABSTRACT

Geotechnical Baseline Reports (GBRs) have been adopted as a tool to balance geological risk and cost of construction projects between the client and the contractor. Over the past five years, application of GBR in Hong Kong construction projects was initiated with tunnelling works. However, recently, GBRs are being adopted in other construction works, such as deep excavation and foundation projects, to define what the expected ground conditions are and as risk allocation tools.

This paper discusses the applications of GBRs on three different deep excavation and foundation projects in Hong Kong. These include case studies on (1) bulk excavation and slope stability of a deep excavation project; (2) diaphragm wall construction of an underground structure; and (3) construction of a bridge. The baselines approaches for key geotechnical issues which may induce significant impacts to the works of the aforesaid projects are discussed.

1 INTRODUCTION

The demand of housing supply in Hong Kong has been rising continuously in the past few years. It is foreseeable that more buildings and associated facilities such as transportation systems will have to be built to satisfy the need of the society. Constructions of buildings and associated facilities commonly involve deep excavation and foundation installation. In many cases, the risks of encountering adverse ground conditions went to the contractors and resulted with high contract prices and/or arguments on claims.

Geotechnical Baseline Reports (GBRs) have been adopted as a tool to balance geological risk and cost of construction projects between the client and the contractor. Over the past five years, application of GBRs in Hong Kong construction projects was mainly associated with tunnelling works. However, recently, GBRs have also been more commonly adopted in other construction works, such as deep excavation and foundation projects, to define what the expected ground conditions are and as risk allocation tools.

The purpose of a GBR is to define ground conditions and that are to be included in the contract as contractual statements (i.e. baselines). Risks related to ground conditions consistent with or less adverse than the baselines are allocated to the contractors, and those significantly more adverse than the baselines are to be accepted by the clients.

The GBR should provide baselines for ground conditions that are contemplated by the proposed works. As the key parts of the GBR, baselined items should be related to those ground characteristics, ground conditions, geotechnical parameters and values that would affect the cost and time for the construction. This should take into account the ground conditions assumed in the design and in the selection of construction methods and plants. The baseline items should be quantifiable and, for the purposes of good definition of the baselined items, there should preferably be sufficient data to form representative database for assessing the baseline ranges or values (although in the extreme case one can baseline an item for which there is no data and the contract is based on the assumed values. If the ground is found to be outside the baseline then the change has to be evaluated). The baselined items should be determinable on site during construction.