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Supporting Tunnelling Excavation of an Unstable Slope by Long Term Displacement Monitoring

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SUPPORTING TUNNELLING EXCAVATION OF AN UNSTABLE SLOPE BY LONG TERM DISPLACEMENT MONITORING

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ABSTRACT

A complex multi-sensor monitoring platform for the continuous control of an unstable slope affected by tunneling excavation, was realized between 2007 and 2008 after the first collapse of an already built tunnel entrance. The monitoring system was made of some inclinometric and piezometric sensors up to 70 m deep, a topographic system, a Terrestrial SAR Interferometer, a weather station, a photocamera and some load cells installed on bulkheads anchors. The continuous monitoring of the slope during different working phases (planning of stabilization works, realization of stabilizations works and tunneling excavation) allowed us to continuously control the slope behaviour, thus guaranteeing the operations in safety conditions. Data derived from the displacement monitoring, combined with geological and geomechanical information, allowed us to better define the complex engineering geological model of the slope, thus supporting the design of stabilization works. Furthermore, the real time control by TInSAR allowed us to stop the excavations of the tunnel for three times following the sudden increase of the slope displacement velocity. Stability thresholds of velocity and displacement have been also defined using semi-empirical models on the basis of the collected historical displacement data.

INTRODUCTION

Deformation control during tunneling excavation is becoming over the last decades a basic requirement for both safety purposes and for faster production. The monitoring of deformation may allow to verify if the deformation at the front or in the tunnel are in line with the expected ones. Hence, it is possible to understand if we are excavating under the predicted design condition and, if not, to adopt effective countermeasures.

Italy, together with the Japan has the longest tunnel network in the world, including different types of tunnels and, especially, tunnels excavated in different materials, both hard and soft rock and soil. Over the last 30 years a new tunneling excavation method has became popular, thus substituting the common NATM method. This method, named ADECO-RS (an Italian acronym for “Analysis of controlled Deformation in rock and soil”) (Lunardi, 2008; Tonon, 2010), considers the deformation as the core of the tunneling activity and, therefore, the control of deformations during the excavation is a key requirement for each planning decision, before and during the excavation phase. Together with the ADECO-RS method, several excavation and stabilization solutions have been developed as well as new approaches for the monitoring of deformations. Hence, deformation monitoring is now at the base of a tunneling project.

Furthermore, in case of tunnels crossing an unstable slope several well established traditional monitoring techniques (inclinometers, extensometers, extensor-inclinometers, topographical surveys etc.) are used. Following the great attention given to the observational method, new solutions for the monitoring of slope deformation have been developed in the last years. New branches of deformation monitoring have been created like remote monitoring, i.e. monitoring by lasers, radar etc (Mazzanti, 2012), thus making the monitoring a large and complex science. These techniques are also offering new opportunities such as the deformation monitoring as a tool for investigation purposes (Mazzanti, this volume).

In this paper we synthetize our engineering geological experience developed by the planning and management for more than 4 years of an integrated experimental monitoring system of an unstable slope affected by a past deep landslide (Bozzano et al, 2008, 2011) along which the entrance of a road tunnel was imperatively planned. All the tunneling phases (from the slope stabilization works to the excavation) have been followed by the integrated monitoring platform made of different sensors, among which the geotechnical traditional ones have been coupled with an innovative Terrestrial Synthetic Aperture Radar Interferometer.

MONITORING THE DISPLACEMENT OF A SLOPE AFFECTED BY TUNNELING EXCAVATION

Techniques for the monitoring of slope deformation can be classified in two main categories: contact techniques *vs* remote techniques.

Contact techniques make use of equipments installed directly in contact with the ground/structure and they can measure the compression/extension (extensometers), the in depth-displacement (inclinometers) or the load applied to a cable (load cells). They are the most traditional and, therefore, the most used solutions and they are characterized by the following main features: i) measurement of local deformation (punctual), ii) high precision; iii) possibility to measure underground deformation; iv) low cost. Among the contact techniques for slope monitoring the following may be considered: inclinometers, extensometers. Looking at the structures and tunnel monitoring the following can be also accounted for: extrusometer, clinometer, loadcells, straingauges etc.

Remote (non contact) techniques make use of active (emitting waves and receiving the reflection) or passive sensors (receiving natural emission) installed far from the monitoring sites and can measure the displacement of single points or large areas. They are the most recent solutions and, if integrated with standard techniques, may improve the quantity and quality of information as follows: i) simultaneous monitoring of an entire slope (information density); ii) high accuracy. Among the remote techniques the following are the most common: GPS, RTS, TInSAR, SInSAR, TLS (see at Mazzanti 2012 for an extensive review).

When looking to the continuous control of a slope affected by tunneling excavation the following main requirements must be satisfied for both safety of workers and high quality plan check during the activities:

a) redundancy on information, i.e. similar data deriving from different and independent techniques allow to improve the trust in the achieved results and reduce the risk to loose information;
b) automatic data acquisition and easy data management and data handling. This allows to collect a large amount of data, independently from the operator ability and availability, and to easily distribute the data to all persons responsible for the tunneling project;
c) high data sampling rate (calibrated with the expected instability behaviour), thus allowing a detailed reconstruction of deformation patterns and to perform accurate forecasting of future behaviour;
d) spread view of the overall slope, thus accounting for all the possible scenarios (i.e. different size of instability events) potentially affecting the tunnel and making it easy to interpret the achieved results;
e) collecting information on both the underground and the surface behavior, thus better understanding the instability process;
f) having at least one remote technique, thus allowing a control of the slope behavior after eventual crisis or when the site is not accessible;
g) simultaneous control of both the ground behaviour and the behavior of underground or surface structures (e.g. bulkheads, walls, gabions etc), thus understanding the ground structure interaction and better interpreting the ongoing processes.

Above mentioned requirements may only be satisfied by a monitoring network integrating different techniques. At the international level there are many examples of slopes whose evolution is continuously monitored by integrated monitoring networks for safety purposes (only to cite some of them: Wieczorek et al, 1990; Varnes et al, 1996; Coe et alii, 2003; Jaboyedoff et alii, 2004; Intrieri et al, 2012; Loew et al, 2012). Some of the above mentioned cases are equipped also by real time alert systems.

THE CASE STUDY

It is well known that large parts of Italy is affected by a high landslide hazard (Trigila et al., 2010). In recent years, the modernization of both motorway and railway national network faces, in several cases, with problems derived from the impact of tunneling excavation on unstable slopes (Lunardi et al., 2008) .

The case study described in this paper concerns a section of a major road imperatively planned on an unstable slope that is characterized by very complex geological and geomorphological features. Few years ago (March 2007), during some preliminary works, an unexpected shallow translational landslide (with a volume of about 10^4 m^3) affected the slope, thus completely destroying the already constructed structures. The landslide involved a steep relief consisting of jointed and weathered metamorphic rocks. A Pliocene and Pleistocene sandy marine deposit overlies most of the elevated portion of these rocks, while sandy colluvial deposits a few meters thick constitute an irregular blanket along the slope (Bozzano et al, 2011). Following this event, detailed geological-engineering investigations and surveys were carried out, thus allowing to obtain a detailed geological model able to explain the occurrence of this landslide.

Geological and geomorphological evidences of an old deep rotational slide that involved a total volume of about $1{\cdot}10^6$ m^3 were identified along the slope: a main sliding surface (up to 50 m deep) and some secondary surfaces were reconstructed by means of dedicated surveys.

Furthermore, several minor shallow translational landslides have been surveyed in the middle-lower part of the pre-existing largest landslide. They involved volumes of about $1{\cdot}10^4$ m^3 of colluvial deposits and bedrock. Among these, we included the landslide that destroyed the already-built structures.

The above described geological model was used as a conceptual basis for the plan of the stabilization works. According to this model, the reactivation of both the whole old landslide and part of it have been taken into account during the planning of the interventions works along the slope. Slope re-profiling, three anchored bulkheads and a surface drainage were mainly realized in order to stabilize the shallow part of the slope, while any structural intervention was planned for the stabilization of the deep part. In addiction to structural interventions, a continuous monitoring platform supporting the working activities was realized, thus allowing to:

a) continuously monitor the evolution of the slope under both undisturbed conditions and during the realization of stabilization works and tunnel excavations;
b) predict the occurrence of critical conditions, if any;
c) optimize planning and construction activities;
d) protect the construction site personnel.

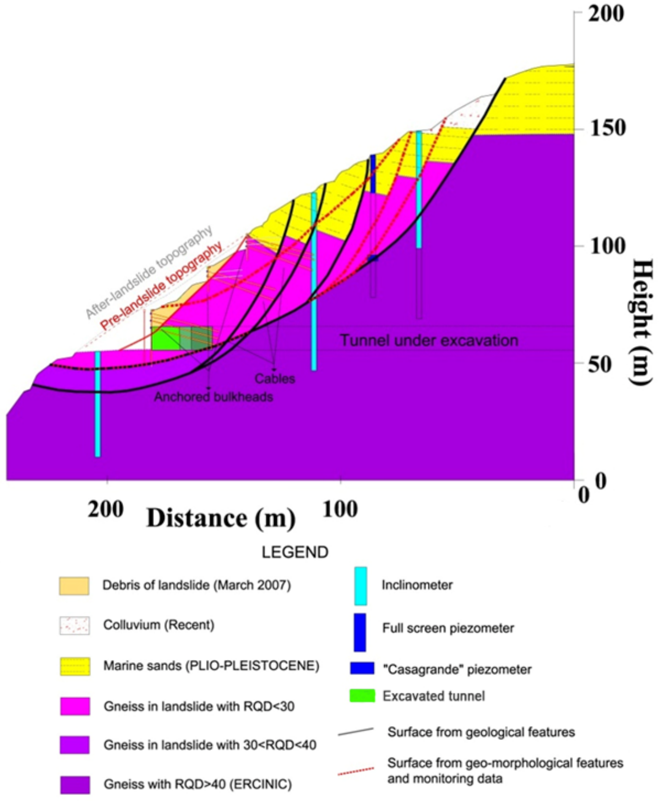

Fig. 1. Geological cross section of the landslide with the identification of realized stabilization structures.

THE MONITORING NETWORK

In order to fill all the requirements listed above, and considering the specific site conditions, an integrated monitoring network was realized (Fig.2). The network, installed in 2007, consists of the following equipments:

- 4 load cells for the monitoring of the anchors installed on the bulkheads during their construction (active from September 2008);
- 3 inclinometers installed on the slope at depth of 50, 75 and 43m b.g.l., respectively (active from June 2007);
- one full screen piezometer installed on the slope at depth of 16.5m b.g.l. (active from June 2007);
- one 'Casagrande' piezometer installed on the slope at depth of 47.5m b.g.l. (active from June 2007);
- about 20 topographic prisms installed on the bulkheads and monitored by total station (active from September 2008).

Apart from above listed standard monitoring systems located on the unstable slope, a remote platform was also realized in a slope located in front of the monitored one at a distance ranging from 700 to 900 m (Bozzano et al, 2008). This system was completed and activated in November 2007 and it was made of the following equipments: i) one automatic weather station (including pluviometer, barometer, thermometer, hygrometer etc.); ii) one automatic camera looking at the slope and especially iii) one Terrestrial SAR Interferometer (TInSAR) model IBIS-L (IDS S.p.A.).

TInSAR represented the more advanced technique used in this case study and it allowed to monitor the surface displacements of the whole slope with a pixel resolution of few meters and a temporal sampling frequency of 5 minutes.

In 2011 the monitoring system was implemented by some inclinometers, herein not dealt with.

MAIN INSTABILTY EVENTS OCCURRED DURING THE WORKING PHASES

After the collapse occurred on March 2007 an intense plan of activities was designed in order to stabilize the slope, to built the entrance and to excavate the tunnel. Unfortunately, several instability problems occurred during the different phases, thus delaying the expected closure of the work. In Table 1 the most relevant working phases and related slope instabilities events are reported. All these instabilities were monitored by the described monitoring system.

After the excavation of a 30 m long tunnel, while the tunneling was approaching the large landslide basal surface, high deformations of the overall slope were observed, thus leading also to the partial rupture of some anchored bulkheads. Following these events, tunnel excavation and other activities on the slope were completely stopped and a new plan for a massive stabilization of the overall slope (including the deepest part) begun. At present such activity is still ongoing.

MAIN ACHIEVEMENTS

The back evaluation of the achieved results suggests the usefulness of the monitoring network to the herein discussed tunneling project.

The main achievements are here organized on the basis of the temporal evolution of the project as follows:

- planning of stabilization activities;
- realization of stabilization interventions;
- tunneling excavation.

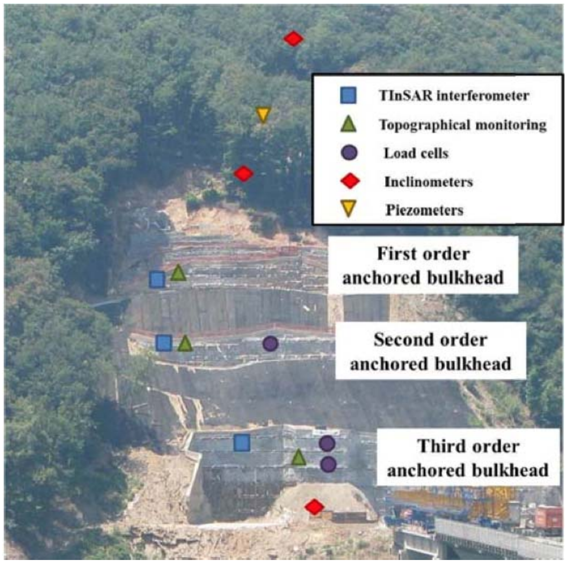

Fig. 2. Main monitoring sensors installed on the slope and some of the points continuously controlled by TInSAR (from Bozzano et al, 2011).

Table 1. Main instability phenomena occurred during the monitoring activity and related working activities on the slope.

Period	Activities	Monitored instability events
March 2007 – April 2008	Minor activities in order to reduce the instability of the post-landslide slope (impermeable sheets, basal wall etc)	Some deformations in a perched residual part of the 2007 landslide and some small collapses, especially at the foot of the 2007 landslide
March 2007 – July 2011	Realization and maintenance of service construction roads	Occurrence of several shallow landslides affecting the roads
April 2008 – January 2009	Excavation of the upper part of the slope aiming at remove the perched unstable deposit and to realize the structural bulkheads	Displacement of the debris due to the excavation and deformation and collapse of the retaining wall at base
May 2008 - July 2011	Realization and maintenance of gabions	Displacement of gabions after their realization and during intense rainfalls
October 2008 – July 2011	Realization and maintenance of anchored bulkheads	Displacement due to the tunnel excavation phases
November 2009 – February 2010	Tunnel excavation	Displacement of the entire slope

Planning of stabilization activities

The planning of stabilization interventions were supported by the results derived from the continuous monitoring which allowed to refine the engineering geological model of the slope. In what follows some examples are presented.

In early 2008, before the start of stabilization works, movements up to 1 cm/day on the area affected by the March 2007 landslide were identified by Terrestrial SAR Interferometry monitoring. Specifically, movement were localized in a perched deposit partially released by the previous landslide (whose volume was on the order of some 100 m^2) and it occurred between November 10th, 2007 and Febraury 29th, 2008. During this time a total amount of about 250 mm along the LOS (Line Of Sight Displacement in Fig.3) were measured. Furthermore, the movement rate increased during intense rainfalls, thus demonstrating a direct link between infiltration and instabilities. On the basis of this result, confirmed by field evidences of small cracks on the slope surface, countermeasures were taken, like the positioning of impermeable layers on the surface, in order to avoid water infiltration. Moreover, the identification of unstable zones was useful in order to identify the best technical solution for the preliminary excavation activities on the slope.

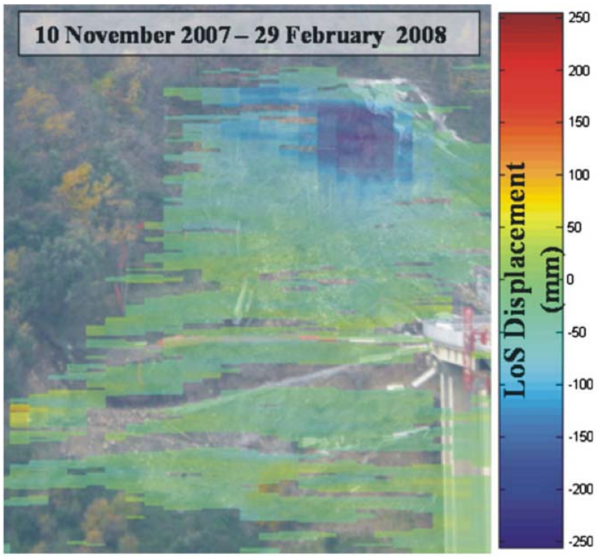

Fig. 3. Picture of the perched deposit overlaid by the TInSAR displacement maps collected from 10th November 2007 to 29th February 2008 (from Bozzano et al, 2011).

Data collected by the three inclinometers allowed us to confirm the presence of some of the already hypothesized sliding surfaces and to document their partial reactivation (see geological profile of Fig. 1 where they are marked by the red color). This information allowed us to re-address the planning of the successive stabilization works.

The widespread monitoring of surface displacement performed by TInSAR allowed to understand that the right portion of the slope was more largely affected by shallow instability than the left one, thus suggesting a heterogeneous slope pattern and, therefore, some internal deformation. Such hypothesis, originally derived from monitoring data, were confirmed by geological and geotechnical surveys (e.g. boreholes) performed in 2010.

Back analysis of some 10 shallow landslides (see an example at Fig.4) occurred in the monitoring period allowed to develop and calibrate numerical and mathematical models for the time of failure prediction (Fig.5). Furthermore, data collected allowed also to understand the main predisposing and triggering factors of these landslides (Mazzanti et al, 2011).

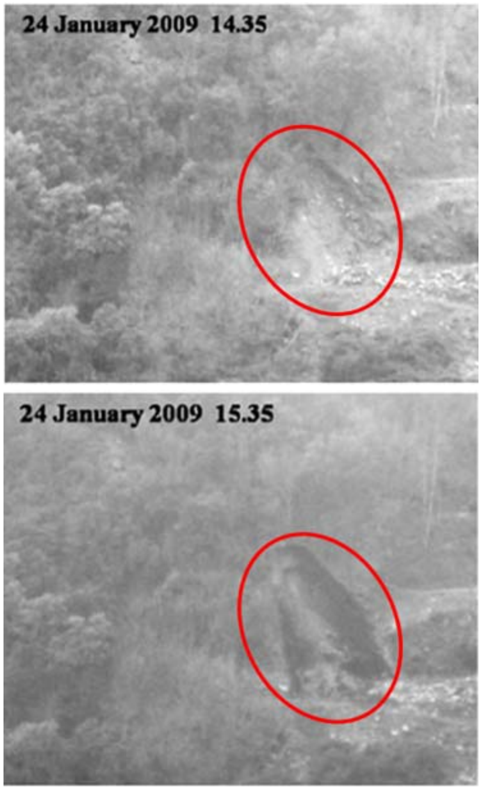

Fig. 4. Picture of one shallow landslide (enclosed by the red ellipse) occurred the 24th January 2009 between 14:35 and 15:35 (modified from Bozzano et al, 2011).

Realization of stabilization interventions

In April 2008, works for the stabilization of the shallow part of the slope started. Specifically, excavation for re-profiling purposes, were carried out. During this phase, the Terrestrial SAR Interferometer allowed to continuously control the downslope movement of the debris and its behaviour in connection with excavation phases and rainfalls (Bozzano et al, 2011) (Fig.6).

Specifically, a total LOS displacement up to 5,6 m was recorded from the beginning of the excavation (April 2008) until its end (January 2009), with a maximum rate of displacement of about 200 mm/day. The instantaneous response of the surface debris movement to rainfall is also clearly visible in Figure 6. The displacement was spatially constant in the entire area covered by the debris with some peaks in sectors characterized by higher thickness of deposit and higher excavation upslope.

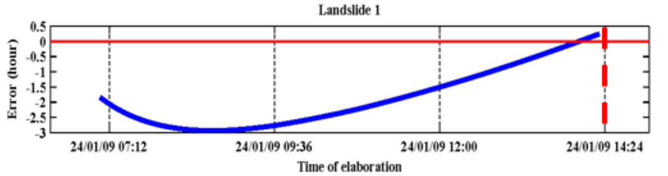

Fig. 5. Time of failure prediction accuracy *vs* time of the landslide showed in Figure 4. In the y axis the difference (error) between the predicted time of failure and the real one. Red horizontal line marks the exact prediction (error=0). The blue line marks the prediction error over time approaching the time of failure (red dashed vertical line). (Modified from Mazzanti et al, 2011).

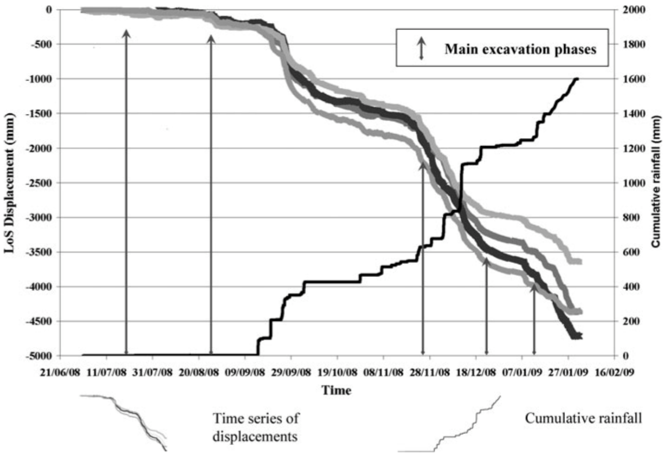

Fig. 6. Cumulative rainfall and displacement time series (June 21, 2008 to January 31, 2009) of some pixels located in the area covered by excavated debris. The black vertical arrows identify the main excavation phases (from Bozzano et al, 2011).

Terrestrial SAR Interferometer allowed also to continuously measure the reaction of the retaining wall built in the lower part of the slope to protect the downslope road, thus allowing to identify its initial movements (due to the debris thrust) and to predict its expected time of failure. Such an information was useful to manage the movement of the working machines in the constructions road located below the retaining wall.

The monitoring by Terrestrial SAR Interferometry allowed also to check the behaviour of the deformable structures, i.e. the gabions, that were built above the constructions roads, in order to stabilize vertical cuts. This information was very useful both for safety purposes and for the gabions management. As a matter of fact, unexpected deformation of gabions were used as indicators of localized conditions where the maintenance of the structures were needed.

Tunneling excavation.

The most important contribution provided by the continuous monitoring system is probably the control of the three anchored bulkheads, i.e. the main structures responsible for the overall slope stability. As a matter of fact, thanks to the deep anchors up to 15m long, they represented the deepest structural intervention of the slope.

Bulkheads were continuously monitored by TInSAR, Total Station and load cells, thus allowing to achieve comprehensive and redundant displacement information. Data derived by the different sensors allowed to identify the sectors affected by unexpected displacements, thus helping in the management and maintenance of the structure. Furthermore, detailed data collected during displacement phases (related to tunneling excavation) allowed us to define the displacement and velocity thresholds for the bulkheads stability (Bozzano et al, 2011). Such a result is demonstrated to be very useful for safety purposes and decision making during activities. As a matter of fact, tunneling excavation was stopped three times following displacement of the slope higher than pre-defined thresholds, thus avoiding the general collapse of the slope (Fig.7).

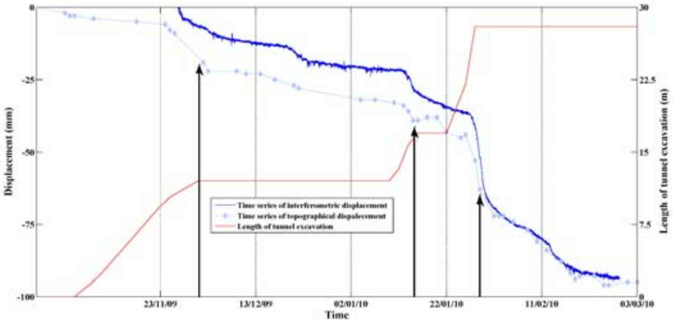

Fig. 7. Displacement time series of anchored bulkheads collected by TInSAR (blue full line) and topographic system (light blue dotted line), and tunnel excavation length *vs* time (red line). Black arrows mark the three excavation stops suggested on the basis of the displacement monitoring data.

CONCLUDING REMARKS

The herein presented case history demonstrates that tunneling excavation of an unstable slope may take advantage by a suitably organized monitoring system. Specifically, plan, execution and management of tunneling phase can be effectively supported by monitoring data. Furthermore, the combination of conventional geotechnical techniques and innovative remote sensing techniques can significantly reduce the uncertainties and increase the amount of useful information. At this regard, Terrestrial SAR Interferometry has demonstrated to be a very effective solution since it is able to provide a widespread view, high accuracy and fully remote capability (Mazzanti, this volume).

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