Satellite InSAR monitoring in urban tunneling projects

TT2018 – TAC/NASTT-NW
Tunnelling & Trenchless Conference

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ABSTRACT

Satellite radar interferometry (InSAR) has been widely applied during all phases (design, construction, and operation) of tunneling projects for monitoring ground deformation in both urban and nonurban areas. In urban contexts, which are particularly sensitive to any ground deformation associated with tunneling activities, InSAR significantly improves the quality of any monitoring program by refining in situ observations. The high density of "natural targets" or measurement points obtained with SqueeSAR processing means there is no need for installation of ground-based instruments. Wide-area coverage provides a synoptic view that extends well beyond the immediate surroundings of the tunnel, where most in situ instrumentation is concentrated. This helps identify and monitor unexpected deformation (e.g. from dewatering) away from the tunnel alignment during the construction phase, or residual deformation after work completion. The processing of historical satellite data archives acquired over the last two decades provides a ground deformation baseline (e.g. identification of pre-existing ground movement) and contributes to estimating the impact of tunneling activities.

Applications of InSAR in tunneling projects will be presented, illustrating the advantages of integrating InSAR monitoring into all phases of the construction.

1 INTRODUCTION

Monitoring surface deformation is fundamental for mitigating risks related to tunneling projects during all phases, from design to construction and operation. The instrumentation used for surface deformation monitoring in and around tunneling sites is generally based on conventional survey techniques (total stations, levelling, GPS receivers, extensometers) however none of these offer the high density, bird's eye view of the movement areas provided by satellite radar interferometry (InSAR).

The complementary use of space-based InSAR with traditional systems has been successfully applied in tunneling projects worldwide, proving to be a strategic tool for detecting unexpected deformations and managing risks. Recently, InSAR has been also included in the "ITAtech Guidelines for Remote Measurements Monitoring Systems", providing recommendations to assist tunnel designers, contractors and owners in understanding the benefits of including remote sensing techniques in their geotechnical monitoring plans.

After a brief introduction to InSAR techniques, this paper presents an overview of applications of InSAR in tunneling projects.

2 INSAR TECHNOLOGY

SAR Interferometry (InSAR) is a remote sensing technology that provides measurements of ground displacements (Gabriel et al., 1989; Massonnet and Feigl,1998; Rosen et al., 2000; Bamler and Hartl, 1998). Radar sensors mounted on satellites acquire images of the Earth's surface by emitting electromagnetic waves and analyzing the reflected signal. Basic InSAR techniques consist of comparing the phase values of two SAR images, acquired at different times with similar looking angles. The phase difference is proportional to the target motion occurring along the sensor-target line-of-sight (LOS) direction during that time interval (Figure 1). As SAR satellites are continuously circumnavigating the globe, a number of radar images can be collected for the same area over time and information about the evolution of the earth's surface can be extracted.

In the late nineties, new Advanced DInSAR (A-DInSAR) techniques emerged in order to estimate and remove the atmospheric noises that affect basic DInSAR data and provide more accurate displacement measurements (sub-millimeter precision) by processing multiple images acquired over the same area over time. Permanent Scatterer Interferometry, the first A-DInSAR technique, identifies and monitors point-wise permanent scatterers (PS), pixels that display both stable amplitude and a coherent phase throughout every image of the dataset (Ferretti et al. 2000, 2001). PS are related to natural radar targets such as manmade structures (buildings, street lights, transmission towers, etc.) as well as rocky outcrops, un-vegetated Earth surfaces, boulders, and any linear structure that can reflect a signal back to the satellite. In order to detect the highest possible density of measurement points in non-urban areas, a new technique known as SqueeSAR™ was presented by Ferretti et al. in 2011, which extracts information from distributed scatterers (DS). This extends measurement point coverage to areas with limited infrastructure and light vegetation. Together, these two types of measurement points form a ground network of radar benchmarks, similar to a GPS (Global Positioning System) network and can be used for monitoring both the displacement of individual structures (a building, for instance), and the evolution of a large displacement field affecting hundreds of square kilometers.

The existence of low-resolution SAR data archives going back to the 1990s initially led to the extensive use of InSAR data to perform historical ground deformation analyses to assess any pre-existing ground deformation phenomenon prior to the design phase of a road or tunnel project. More recently, the use of high-resolution sensors has considerably increased the density of detectable information, up to thousands of measurement points per square kilometer in urban areas (Figure 2). In conjunction with this, the launch of satellites with a high frequency of acquisitions (up to a few days), combined with the development of sophisticated automatic processing algorithms made it possible to continuously provide reliable surface deformation measurements with each new satellite image (Raspini et al., 2018).

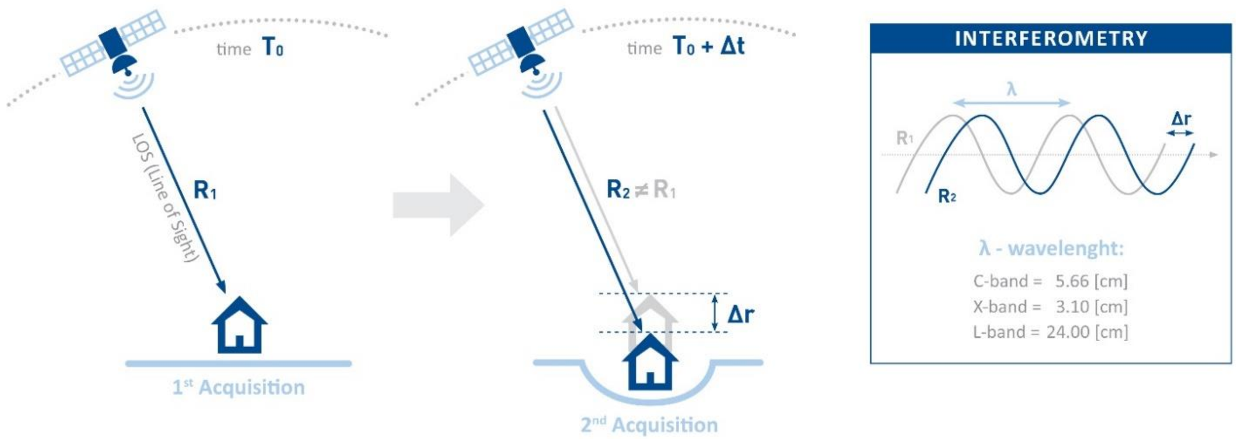

Figure 1. An illustration showing the relationship between ground displacement and signal phase shift. This is the basic principle of InSAR for measuring ground movement.

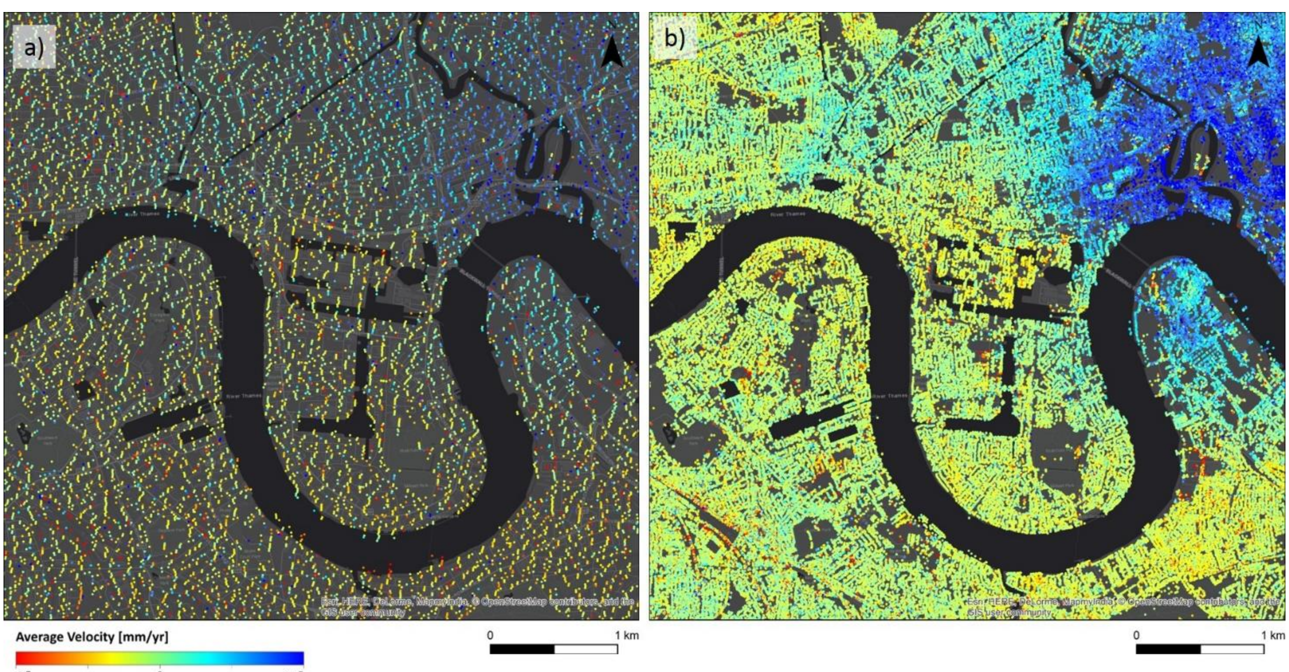

Figure 2. From Bischoff et al. (2017): Low-resolution Sentinel-1 data (a) and high-resolution TerraSAR-X data (b) over East London, demonstrating agreement in regional displacement patterns despite the point density differences. Uplift in this area (blue) is linked to ground rebound as the water table rose after dewatering for Crossrail works was reduced.

3 INSAR IN TUNNELING APPLICATIONS

The key characteristics of InSAR applications for tunneling projects are:

- The wide coverage and high density of information provided remotely by advanced InSAR techniques is not achievable with in-situ instrumentation. As InSAR is based on the use of natural radar targets that already exist over the ground, the technique provides thousands of measurement points per square km, extending the InSAR view well beyond the immediate surroundings of the construction site or tunnel alignment.
- Historical satellite data archives collected over the last two decades can be processed to detect pre-existing ground movement near the planned alignment or project site in order to estimate the impact of excavation activities.
- The recent launch of satellites with high spatial resolution and high frequency of acquisitions, as well as the recent development of new processing techniques provide near real-time and long-term stability monitoring solutions for monitoring operative tunnels.

Selected case studies will be presented in this section to illustrate the use of satellite radar data during various project stages, from design to construction and operation.

3.1 Gran Paris Express (Paris, France)

During the planning stage of long linear infrastructures, satellite remote-sensing data also offers the advantage of minimizing survey times and costs when covering wide areas.

This is the case of the Grand Paris Express, the largest transport development project in Europe. It consists of a fundamental redesign of the public transport network for the entire Paris metropolitan area, including 68 new stations and 200 kilometers of underground metro lines. Construction work began in mid-June 2016 and is intended to last almost until 2030.

Because of the creation of numerous construction sites, most of them in urban areas and using complex underground drilling techniques, risk assessment and management plays a key role in both the project design and construction phases.

The Société du Grand Paris (SGP) is the public agency set up by the French government in 2010 to deliver the vision of Grand Paris Express. It leads all operations related to the construction of the new metro lines, stations, structures and facilities, acquisition of rolling stock for the infrastructure and development within and around the stations.

From project conception to the execution of the Grand Paris Express, the SGP relies on specialized companies that support it in its role of project owner. In particular SGP commissioned a historical SqueeSAR analysis to detect any pre-existing movement affecting over the 200 km of the Grand Paris Express network alignment from April 1992 to March 2015 (Urdiroz et al. 2014).

The historical ground motion analysis included the processing of low-resolution satellite images (from the ERS and ENVISAT satellites of the European Space Agency), covering the period 1990-2010, and high-resolution satellite images (from COSMO-SkyMed of the Italian Space Agency and TerraSAR-X of the German Space Agency) over the more recent period 2011-2015 (Figure 3).

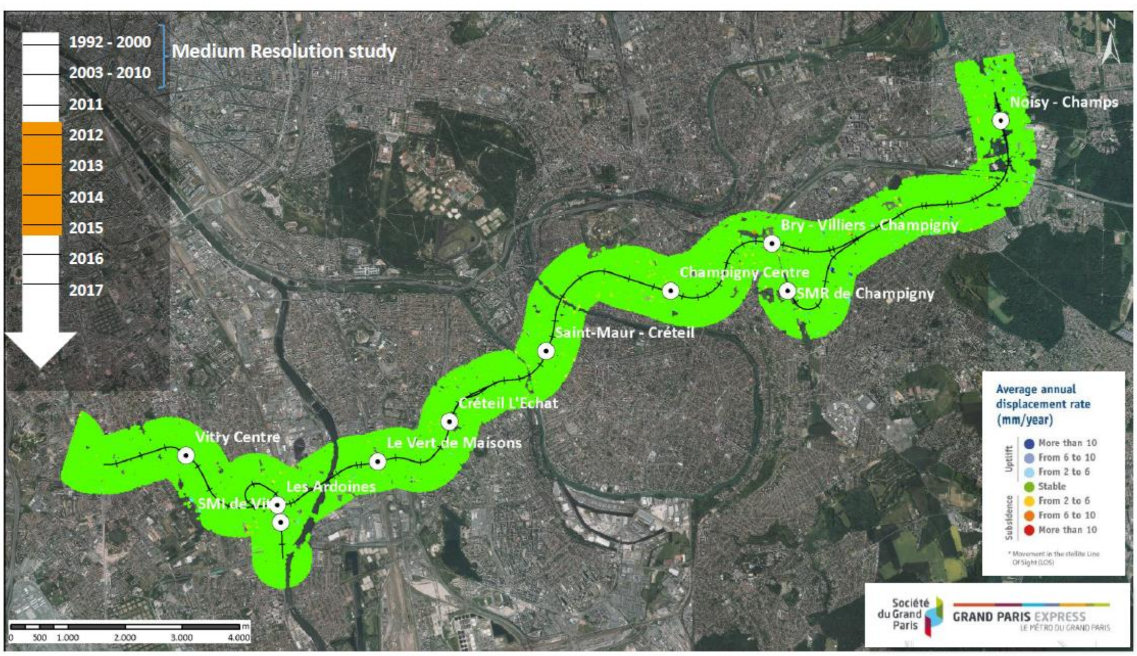

Figure 3. From Koudogbo et al. 2018: Ground motion map over a sector of the Grand Paris Express, generated from the SqueeSAR historical analysis (2011-2015) of high resolution TerraSAR-X images.

This historical analysis has made it possible to create an extensive inventory of the ground surface behaviour and the identification of vulnerable structures before the start of any construction work. In key areas where surface movements were detected, additional ground surveys have been or will be carried out if required to complement geological and geotechnical data.

As the first groundworks started in 2016, the TerraSAR-X high-resolution satellite has been used for detecting and measuring surface deformations related to the progression of the tunnel boring machine and complement the in-situ real time monitoring (precision levelling measurements, inclinometers, etc). Monthly SqueeSAR updates based on a new satellite image every 11 days, provide an unrivalled measurement point density (> 10,000 points/km²) and are specifically designed to monitor the evolution of non-linear motion with a millimeter accuracy over the tunneling sites (Koudogbo et al. 2018).

3.2 High-Speed Railway Station (Bologna, Italy)

In the framework of the high-speed Milan to Naples railway construction in Italy, a tunnelling project under the city of Bologna was recently completed. It is a double-track tunnel with an excavation area of approximately 130m^2. It crosses an urban area at shallow depths (approximately 10m) with a high density of commercial activities and residential buildings.

Considering the delicate urban and geo-technical context and the expected effects induced by the tunnel, a comprehensive in situ monitoring system was combined with satellite remote sensing data during the construction phase (Pigorini et al., 2010). Both RADARSAT-1 satellite data (for the period 2003-2011) and ESA ERS-1 and ERS-2 images (for the period 1992-2000) were used. More than 280 satellite images were processed. After processing the SAR data archive, it was possible to identify a significant deformation trend. The alluvial deposits on which the city of Bologna is built are affected by land subsidence, mainly induced by natural sediment compaction and ground-water exploitation for industrial, residential, and agricultural uses. The effects induced by tunnel construction arose in addition to this pre-existing deformation phenomena. In order to highlight the displacements induced by tunnelling activities alone, a reference point was selected in order to minimize the displacement gradients due to generalised subsidence and to isolate the displacements induced by the excavation works (Figure 4).

Critical analysis of single measurement point displacement time series along with the chronology of the site and tunnel excavation activities (even before initiation of ground works) provided a detailed evaluation of any correlation and other interesting deformation effects that have occurred at on the ground's surface.

Figure 5 shows an example of a displacement time series of a measurement point located near the tunnel centre line. After the first period of the time series (2003-2007), which exhibits general stability, the image shows an increase in the displacement rate during 2007 and 2009-2010, both followed by stable periods. This behaviour is in exact agreement with the site work activities. The first acceleration is related to the construction of 10 micro-tunnels between March and October 2007; the second is related to tunnel advancement in the first months of 2010. In the subsequent period the excavation front was far from this particular measurement point and displacement stopped, coinciding with the stable period at the end of the displacement time series.

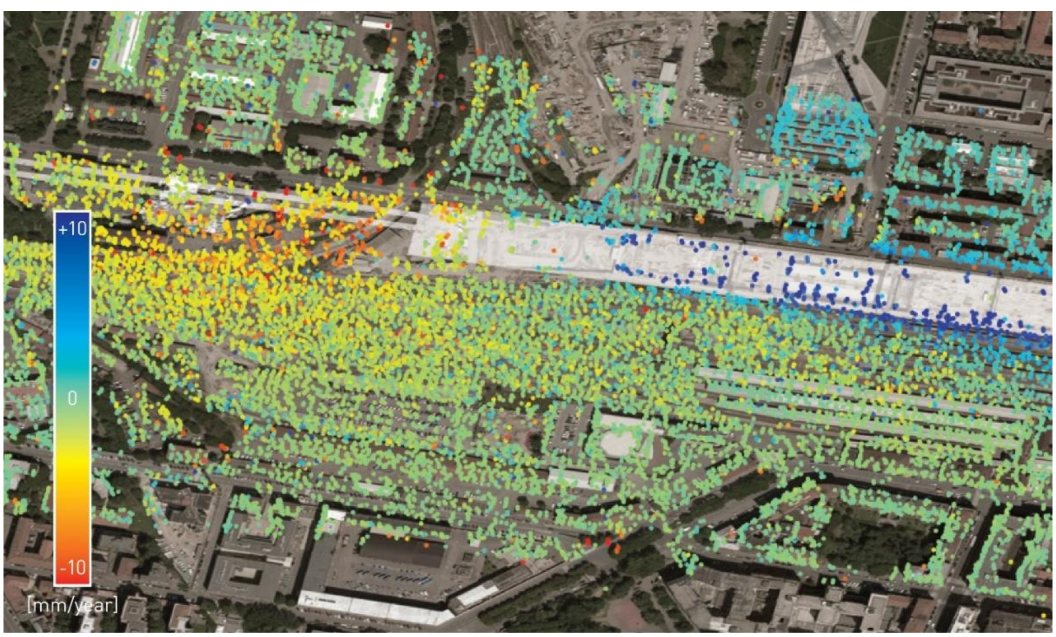

Figure 4. Bologna High-Speed Railway site. The map shows the distribution of the measurement points identified with SqueeSAR, colour coded according to the average displacement rate measured during the construction period.

Subsidence on the left is induced by the tunnel excavations. The uplift on the east side is related to the rebound effect induced by the removal of superficial structures for the construction of the new railway station.

Figure 5. Modified from Pigorini et al. (2010): displacement time series showing the effect of the tunnel excavation.

3.3 Alaskan Way (Seattle, USA)

The Alaskan Way Viaduct Replacement Program in Seattle is a major infrastructure update project along a portion of State Route 99, which passes through Seattle's historic waterfront area. The project includes a 17.4 m diameter, and 2.8 km-long bored tunnel.

In 2014, a 36.5 m deep access shaft was constructed for TBM repairs and it is widely recognized that the associated dewatering work lead to widespread settlement in the dense urban area, which includes several historic buildings. TRE Altamira conducted an InSAR analysis of the period immediately preceding, during and after the dewatering took place (Figure 6).

The ground motion analysis included the processing of high-resolution COSMO-SkyMed satellite images over the period of August 2014 to February 2015. This historical analysis made it possible to create an extensive inventory of the ground surface behaviour during dewatering.

Comparison with piezometric data (Figure 7) showed a very close correlation between aquifer depressurization and subsidence. The dewatering system was activated in the fall of 2014. The InSAR results show a deformation rate of 0.02 mm per day leading up to November 2014. During the month of November, the rate increases to 1.1 mm per day and then decreases to 0.06 mm per day from December 2014 onward. A comparison of piezometric data from the area surrounding the access shaft with the InSAR data coincides in time.

Given the strong impact of dewatering work on subsidence in the area, the InSAR data provided useful insight into the exact spatial extent and boundaries of the area of subsidence during this stage of the tunneling project.

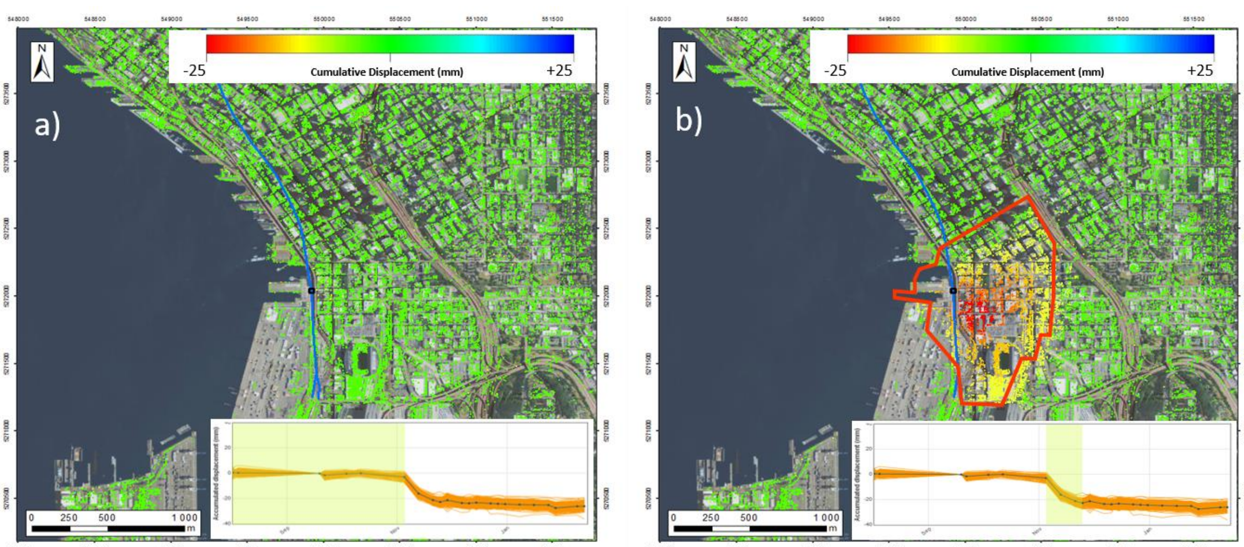

Figure 6. a) InSAR results show relative stability prior to the dewatering work. b) InSAR results show over 20mm of subsidence during the dewatering work.

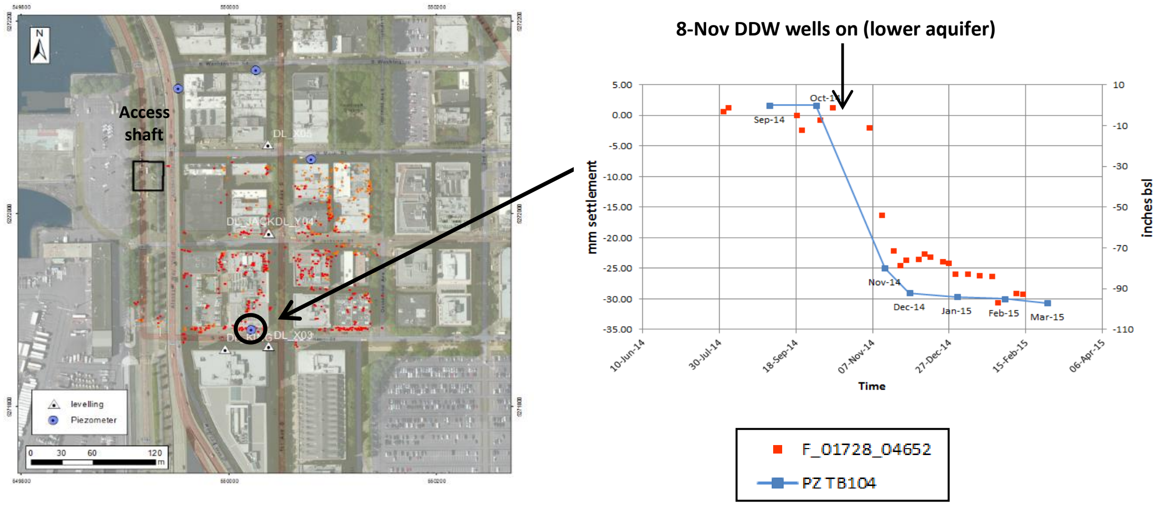

Figure 7. InSAR measurements and piezometric data from the same area to the Southeast of the access shaft.

3.4 A1 Highway (Italy)

A long term SqueeSAR monitoring program is currently active over a portion of the A1 Highway in the central Apennines (Italy), where a deviation project, involving 62.5 km of the highway, was completed in December 2015. The project included the addition of a third lane on each side of the existing highway and the construction of a new section, most of which consisted of viaducts and tunnels, the longest being 8.7 km in length. Now complete, the new section runs parallel to the old motorway and provides an alternative route in order to decrease traffic congestion.

Over one of the tunnel sites, deep-seated quiescent landslides were reactivated during the excavation (Barla et al. 2015). The twin three-lane tunnels, each with a cross-section area of 160 square metres, were excavated full-face by conventional methods. Systematic reinforcement measures by means of fiberglass dowels were applied and the final lining was always kept near the advancing tunnel face. Tunneling took place through a flysch rock mass, consisting of sandstone-mudstone layers with different thickness, with rock mass quality from fair to poor and, in some cases, very poor. The area above the tunnels was heavily monitored during the excavation using inclinometers and piezometers, including a number of robotic total stations for real time monitoring of villages. The two tunnels were excavated with one face preceding the other by 80-100 m, within controlled values of both the convergences of the tunnel perimeter and extrusion deformations ahead of the face.

With evidence of surface and subsurface movements occurring concurrently during tunnel excavation, the decision was taken to activate an InSAR monitoring plan. SAR imagery acquired by three different medium-resolution satellites over more than a decade (2003-2015) was processed with SqueeSAR to reconstruct a history of landslide behavior before construction commenced (Figure 6). After the tunnel completion, a monitoring plan with high-resolution TerraSAR-X images was established that will run until 2020 in order to monitor the post-construction phase.

The displacement time histories of some radar targets are shown in Figure 8, Figure 9 and Figure 10, together with displacement data provided by robotic GPS stations.

A displacement rate of a few mm/year was observed before tunnel excavation, previous to the installation of any other conventional monitoring instrumentation. A sudden acceleration was observed during the excavation activity, starting from 2011 (displacement rate up to 60 mm/year between 2011 and 2013). Surface movement developed progressively and coincided with the tunnel excavation and face advancement, with clear evidence of reactivation of the deep-seated landslides.

After tunneling completion in November 2014, a progressive deceleration started to take place, although complete stabilization over the entire area above the tunnels had not yet been reached at the end of March 2015.

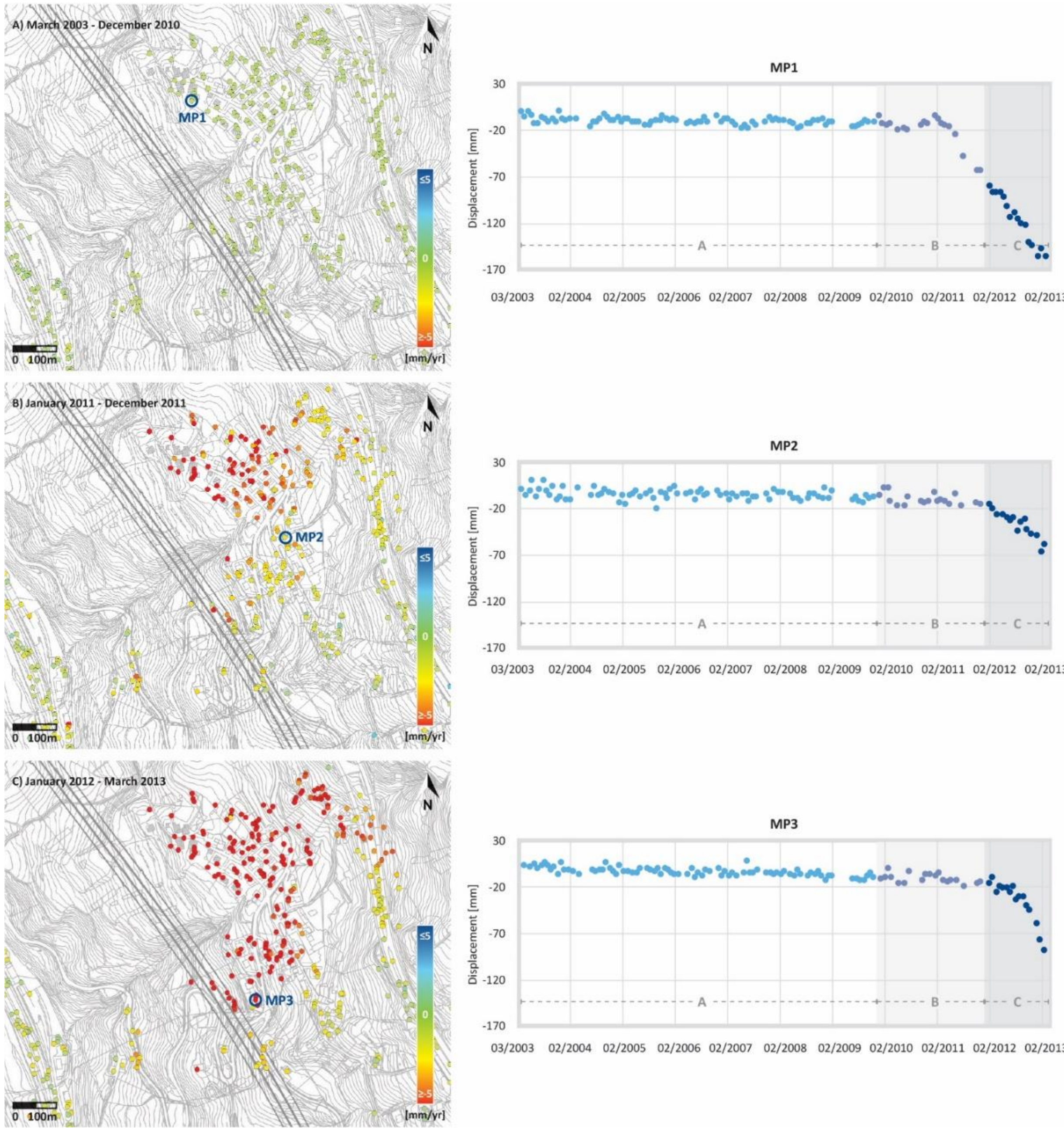

Figure 8. From Barla et al. 2016: Multi-temporal deformation maps over a section of tunnel. Each map represents the average yearly displacement rate for a specific period. On the right the displacement time series of a selection of measurement points are reported.

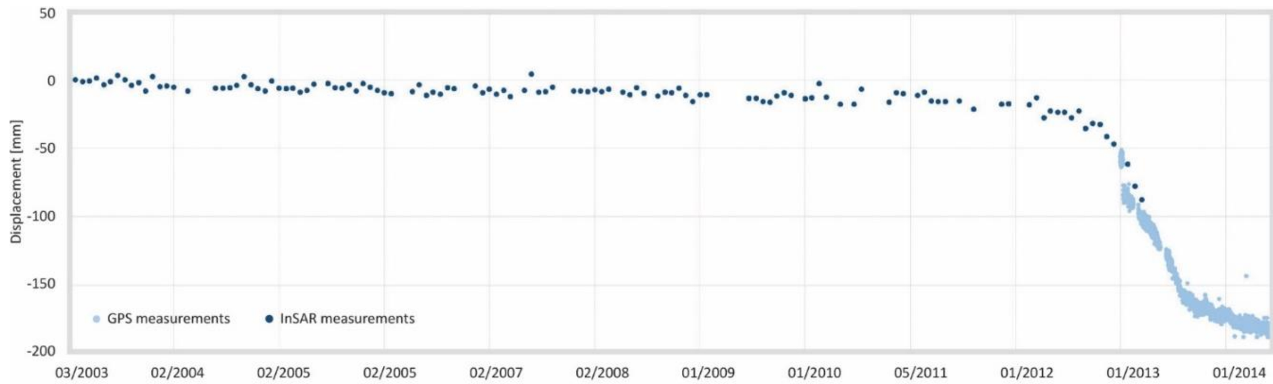

Figure 9. From Barla et al. 2016: InSAR and GPS displacement time-series. InSAR data are obtained by the processing of a descending RADARSAT archive of imagery covering the period March 2003 – March 2013. GPS measurements started in January 2013. The comparison is performed by projecting GPS measurements along the satellite line of sight.

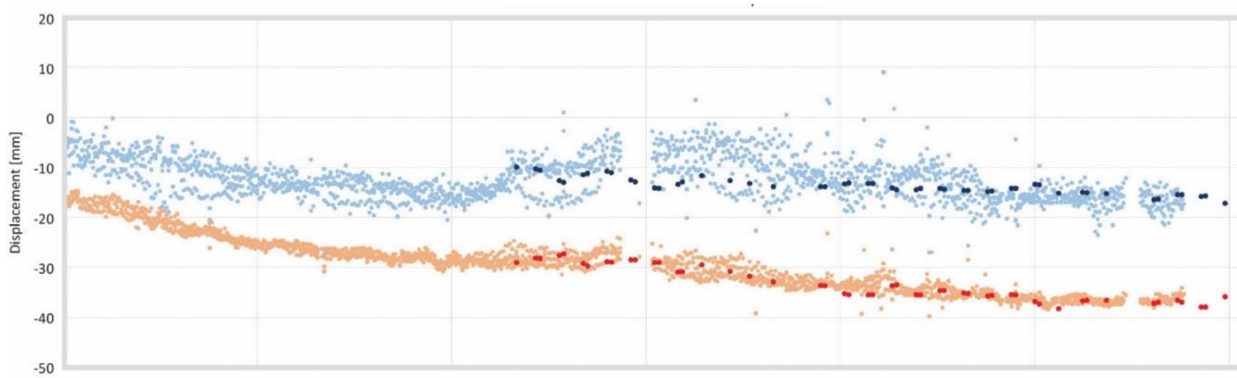

Figure 10. From Barla et al. 2016: GPS and InSAR displacement time-series, vertical (blue) and E-W (red) components. InSAR data are obtained by the combination of ascending and descending TerraSAR-X datasets, covering the period April 2014 – March 2015.

4 CONCLUSION

Increasingly, space-based InSAR is being built into comprehensive geotechnical monitoring programs for tunneling projects as it offers a synoptic, wide-area view, which coupled with localized, traditional in-situ systems offers the most thorough combination of spatially and temporally dense ground deformation data.

The advantages of using this technology has been pointed out through applications in all phases of tunnel projects, from design to excavation and operation.

During the preliminary design phase of any infrastructure project, InSAR can provide historical ground motion information that contributes to the characterization of pre-existing deformation phenomena that can be affect the future infrastructure.

During the construction phase, InSAR is integrated with localized in-situ monitoring instrumentation to monitor a wide area for potential unexpected deformation phenomena that may be linked to the construction works.

Regular monitoring of operational infrastructure supports the maintenance program, helping identify possible structural weaknesses or damage, and provides an early warning of possible accelerations in deformation. Finally, the recent launch of satellites with a high frequency of acquisitions (up to a few days), combined with the development of sophisticated automatic processing algorithms make it possible to provide reliable surface deformation measurements at each new satellite image.

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