Application of satellite radar interferometry for structural damage assessment and monitoring

C. Giannico, A. Ferretti, S. Alberti
TRE – Tele-Rilevamento Europa, Milano, Italy

L. Jurina
Politecnico di Milano, Dipartimento Strutture, Milano, Italy

M. Ricci, A. Sciotti
Italferr – Direzione Tecnica, U.O. Gallerie, Roma, Italy

ABSTRACT: Remote sensing techniques have been widely used in recent decades to monitor earth surface displacements. SqueeSAR™ SAR interferometry is today one of the most advanced technologies for surface deformation monitoring. It exploits long temporal series of satellite radar data, acquired over the same area of interest at different times, to identify "natural radar targets" where very precise displacement information can be retrieved. Selected case studies will be presented, demonstrating how satellite radar data can provide useful information during the various stages of infrastructure construction, from design to building and management. Applications carried out in urban contexts demonstrated that satellite interferometry is not only suitable for monitoring slow and constant-velocity movements, but can successfully work even in case of abrupt changes and significant variations in displacement rate through time. In about ten years from its development, this technology has become a standard monitoring tool used as an integration with ground based monitoring techniques.

1 INTRODUCTION

Since 1978, the first radar images of the Earth's surface obtained from Synthetic Aperture Radar (SAR) sensors mounted on satellites have stirred significant interest in the sector of Earth Observation, creating new ground monitoring opportunities for analysis of surface deformation phenomena.

In the late 90's a new technique was developed by the Department of Electronics at the Polytechnic University of Milan and then further by Tele-Rilevamento Europa, its first spin-off company. Research and development of the permanent scatterers (PS) and PSInSAR™ (Ferretti et al. 2001) techniques are patented, including the recent evolution of the SqueeSAR™ algorithm (Ferretti et al. 2010).

Over the last few years, PSInSAR™ (now SqueeSAR™) has become an extremely useful tool for studying and monitoring the territory and is today commonly used both in Italy and abroad for civil protection applications by regional governments, water authorities, research centres and numerous companies in varying market sectors (e.g. oil&gas, utility, construction, etc.). The new data sources now available (X-band data) as well as new algorithms recently developed changed the scenario of the application of PSInSAR™ data to the monitoring of individual buildings and single structures.

2 MONITORING TECHNOLOGY

Radar satellites allow the measurement of ground displacement to millimeter accuracy, thanks to a particular technique known as the 'multi interferogram' approach. The latest development of this technique is SqueeSAR™, which allows the identification of discrete ground points and their displacement in time.

Analysis of ground displacement is possible due to the exploitation of data obtained from all radar systems: the distance between the sensor and an 'illuminated' target.

In this particular case, synthetic aperture radar (SAR) satellites regularly retrace the same orbit, allowing a sequence of temporally spaced images to be acquired over the same area. The basic idea is to compare successive satellite images, measuring the sensor-ground point distance, with the objective of measuring ground displacement (Fig. 1).

Measurements are only possible when ground points have specific electromagnetic characteristics: ground targets are present on the ground surface (scatterers) and are visible in all satellite images acquired throughout the period of observation and have a sufficiently stable 'phase signal' in time (permanent) (Ferretti et al. 2001).

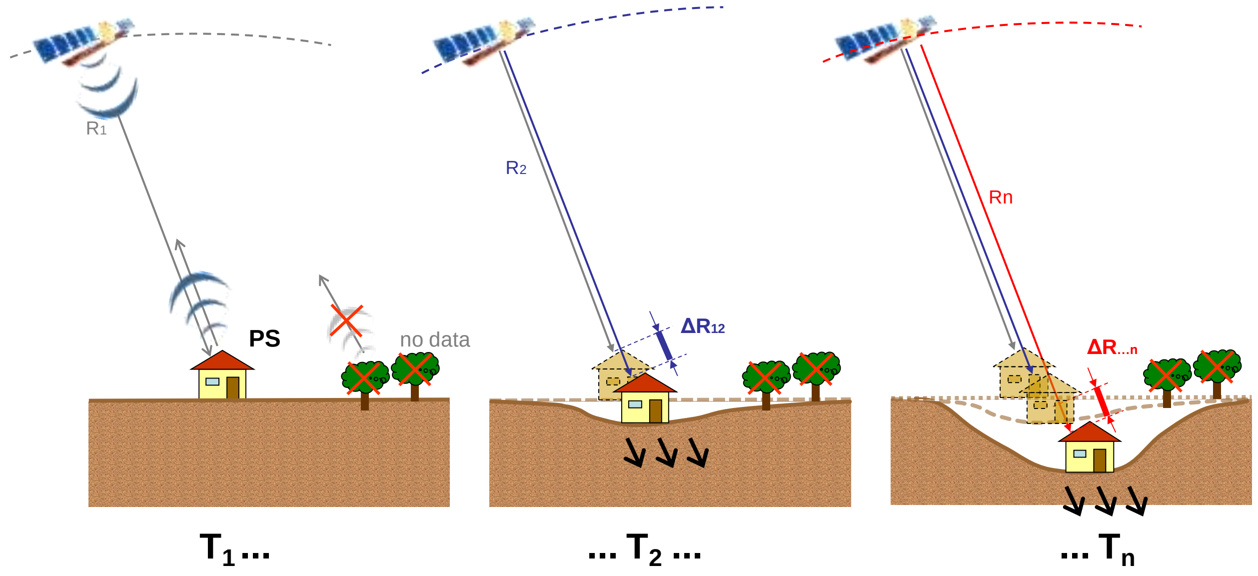

Figure 1. Basic concept of interferometric analysis: comparison between successive measurements of sensor-to-target distance, allowing ground displacement to be determined.

The phase signal is the element that contains information about the position of the ground surface and the distance between the satellite and ground point. As the signal emitted from a satellite has a wavelength of centimetres (microwaves), millimetric ground displacements introduce phase shifts between successive images (e.g. R_{n-1} vs. R_n) which are detected and analysed.

SqueeSAR™ can identify two families of ground measurement points on the Earth's surface:

– Permanent Scatterers (PS): points characterised by high reflectivity and occupying a single pixel in the image, typically corresponding to houses, buildings, metallic objects, pylons, antennae, exposed rock surfaces, pipelines, etc.
– Distributed Scatterers (DS): signals are received from several homogeneous less-strong reflectors over an area covering a number of pixels. These signals correspond to rocky outcrops, detritus, non urban and non vegetated areas.

For each ground point, the following principle information is supplied:

– Position on a reference map, precision up to 1m;
– Average annual velocity of the ground point, with accuracy that can exceed < 1mm / year;
– Time-series of ground point displacement, with accuracy that can exceed < 5mm.

In order to successfully perform a SqueeSAR™ analysis, a minimum number of satellite images (approximately 10-15) are required over the same area of interest. This is necessary to create a reliable statistical base of electromagnetic ground point responses, used to identify which pixels contain usable information and which contain noise. The higher the number of images acquired and processed, the better the results obtained.

Error bars of SqueeSAR™ measurement are extremely complex to be estimated theoretically, before actually processing the data available (Colesanti et al. 2003). In fact, the precision of the displacement measurements depends on many different factors, such as: number of images used for analysis; spatial density of the measurement points (lower the density, higher the error bar); quality of the radar targets (signal-to-noise ratio levels); climatic conditions at the time of the acquisitions; distance between the measurement point and the reference PS; repeat cycle of the satellite (the lower, the better).

An overall picture of the typical precision obtained by SqueeSAR™ analysis is provided in Table 1, which shows the values of standard deviation for average annual velocity, single measurement and positioning in terms of geographical coordinates (North, East, Height).

Table 1. Typical values of precision for a point less than 1 km from the reference point for a dataset of at least 30 scenes spanning a 2-year period

Precision (1σ)	C-band satellite	X-band satellite
Positioning (E-W)	7 m	4 m
Positioning (N-S)	2 m	1 m
Position (Height)	1.5 m	
Average annual velocity	<1 mm/yr	
Single Measurement	<5 mm	

2.1 *Strengths and weaknesses*

SqueeSAR™ is a monitoring tool unique for accuracy, spatial density of measurement points and economic competitiveness. It is not a tool to replace all pre-existing methodologies for measuring surface movement. There are elements of the technology that make it unique, even if there are situations where SqueeSAR™ simply won't work or will produce poor results. Presented here are some of those strengths and weaknesses.

Advantages of SqueeSAR™ technique:

– PS data allow the detection and monitoring of displacement fields with sub-centimetre accuracy

- Whenever the PS density is high enough, the technique does not require the installation of any ground instrumentation
- SqueeSAR™ technique allows to carry out multi-scale analysis. It can be used for regional studies as well as for monitoring individual buildings and structures
- The possibility to process data archives of ESA (European Space Agency) historical data allows to carry out SqueeSAR™ analysis as far back as 1992, enabling a historical review of movements
- PS data are often complimentary to conventional in-situ measurements (such as GPS and optical levelling) (Burgmann et al. 2006)
- PS motion can be measured over areas of thousands of square kilometers at a fraction of the cost of conventional surveys - while achieving much higher spatial densities of measurement data
- The introduction of new X-band SAR sensors allows better spatial resolutions and more frequent acquisitions over an area of interest. These sensors will play a key role for the monitoring of individual structures.

Limitations of SqueeSAR™ technique:

- Vegetation prevents the identification of radar targets and consequently the ability to estimate ground deformation patterns over heavy vegetated areas. The problem can be solved by installing (passive) artificial reflectors, carefully designed to create measurement points
- Measurements of displacements, along the sensor-target direction, are limited to a fraction of the wavelength
- SqueeSAR™ technique cannot measure deformation along the North-South direction, since these movements are parallel to the satellite orbit direction

3 APPLICATION FOR INFRASTRUCTURE DEVELOPMENT

In 2008 Italferr (Italian State Railways Group engineering firm) signed a framework agreement with TRE (the company owning the exclusive patent of PSInSAR™ and SqueeSAR™ technique) that led to a series of applications in the railway sector. These applications have been useful in supporting the infrastructure's entire life cycle (design, construction and operational phases).

Different case studies will be presented with particular reference to applications involving underground works (Scianina tunnel – Tracoccia, Sicily and Bologna railway station). Recent analyses carried out over the worked site of Bologna's railway centre, during the completion of the natural tunnel along the new HS/HC line, provided a useful comparison between the displacement measurements obtained by satellite data and traditional measurement data obtained during the works (Pigorini et al. 2010).

3.1 *Project, construction and monitoring*

During the feasibility and preliminary project phase of any infrastructure, satellite remote-sensing data can offer a useful contribution to the analysis of the area of interest. The identification of unstable areas affected by surface movements and the reconstruction of their displacement over time by means of historical PS analysis (integrated with geological and geo-technical information) allows the reconstruction of a synoptic view of the local dynamics in a geographic information system (GIS), useful for the definition and the planning of railway routes. In the project phase of large linear structures, such as a railway, satellite remote-sensing data offered the advantage of minimizing survey times and costs, compared to other monitoring techniques.

PSInSAR™ technique has been applied in the preliminary design of the new Venice-Trieste railway line (Ronchi-Trieste section), for the assessment of the planned route (Fig. 2). Between Santa Chiara and Trieste, the planned route crosses the coastal slopes and Trieste Flysch formations. The scope of the analysis was to identify areas subject to surface movement, and integrate the results with geological studies and geotechnical surveys.

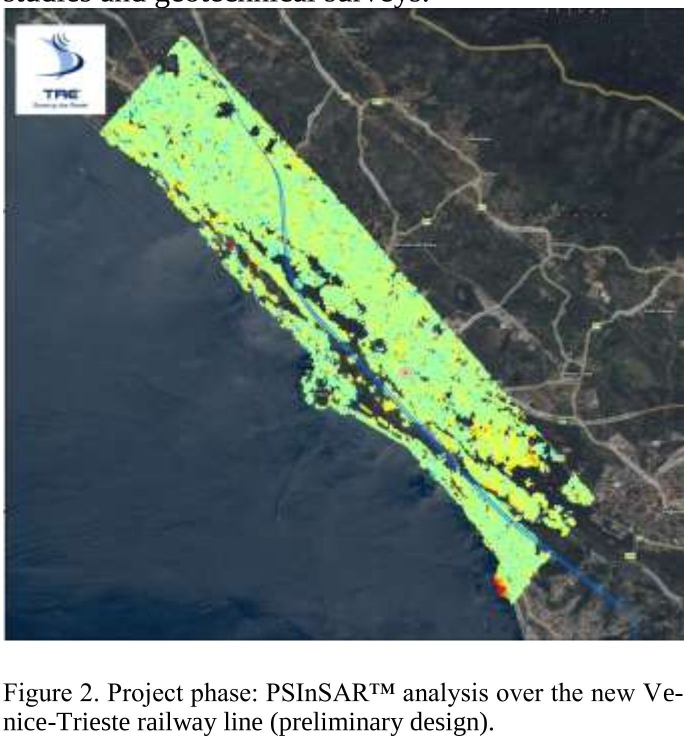

Figure 2. Project phase: PSInSAR™ analysis over the new Venice-Trieste railway line (preliminary design).

In the framework of the high-speed Milan to Naples railway construction, a tunnelling work under the city of Bologna (Italy) has been recently completed. It is a double-track tunnel with an excavation area of approximately 130m^2 , crossing urban surroundings at shallow depths (approximately 10m) with a high density of commercial activities and residential housing (Fig. 3).

Figure 3. Construction phase: Bologna (Italy) area of interest.

Considering the delicate urban and geo-technical context and the expected effects induced by the tunnel, it is evident how, in this specific case, monitoring surface deformation is of utmost importance. During the construction, it was decided to combine the comprehensive *in situ* monitoring system with PSInSAR™ data.

For the PS analysis, 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 in the study area present *before* construction activities commenced (Bonsignore 2007, Carminati et al. 2002). The effects induced by tunnel construction arose in addition to the pre-existing deformation phenomena.

In order to highlight the displacements induced by tunnelling activities alone, it was considered appropriate to select a reference point in such a way to minimize the displacement gradients due to generalised subsidence and to detect the sole displacements induced by the excavation works (Fig. 4).

Critical analysis of single PS displacement time series, along with the chronology of the site and tunnel excavation activities (even before initiation of site works) have provided a detailed evaluation of any interference and other interesting deformation effects that have occurred at ground level.

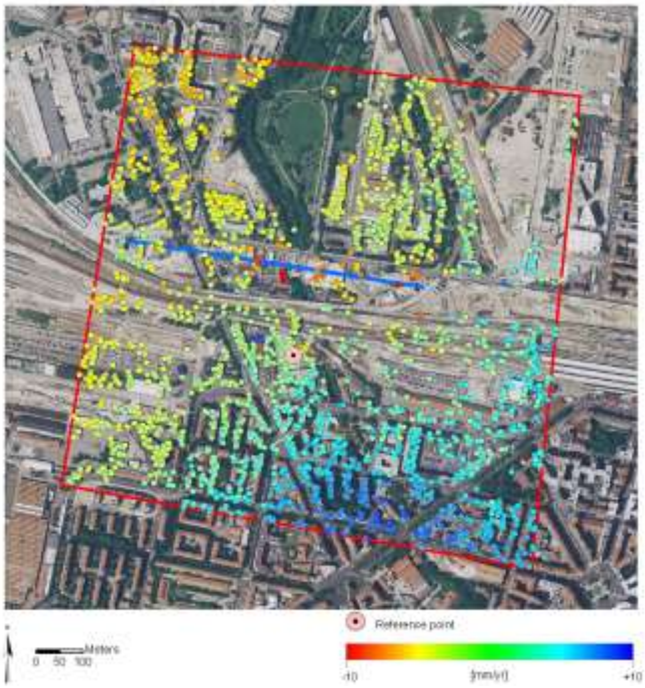

Figure 4. Construction phase: PSInSAR™ analysis over Bologna. PS/DS Average Velocity [mm/yr] along satellite line of sight.

Figure 5 shows an example of a PS time series located near the tunnel centre line, approximately in the centre of the area of interest.

After the first section of the time series (2003-2007) which exhibits displacements of low zero-average ripples, the image shows an increase in the displacement values during 2007 and then during 2009-2010, these displacements are followed by stable periods with zero displacement values until the end of 2011.

This behaviour is in perfect agreement with the site work activities around this point of interest. The first increase in displacement values is related to the construction of 10 micro-tunnels between March and October 2007; the second is related to the tunnel advance in the first months of 2010. In the subsequent period the excavation front was far from the considered PS, and displacement stopped (confirming the final section of the historic time series).

The use of satellite data provided a very useful dataset to be compared with the displacement values measured by in situ instruments. In this case, it was also possible to compare the historical time series of PSInSAR™ data with the settlement rates estimated by optical levelling surveys.

In order to make such a comparison possible, it was necessary to define a common reference point and re-project ground measurements along the satellite line of sight.

The topographic monitoring design refers to a datum point "ARPA 75/020line 324" located in Zanardi street, n.83 (on the building at the corner with De' Carracci street), 400m from the reference point chosen for the satellite analysis.

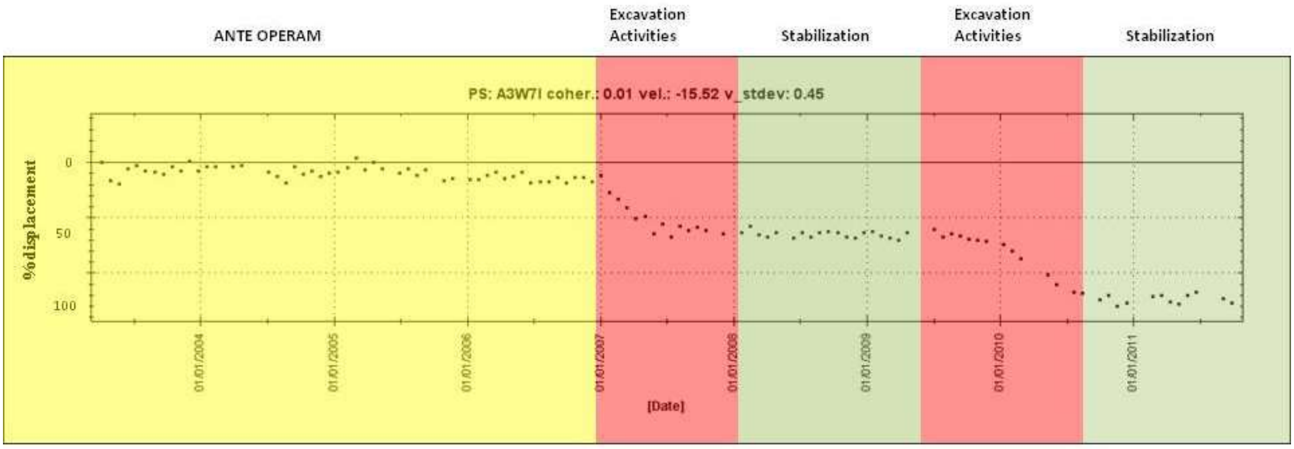

Figure 5. Displacement historic time series representing the effects induced by tunnel excavation.

Figure 6 shows a comparison between another PS time series and the settlement time series of the corresponding topographic levelling benchmark. The optimal correlation between the two data-sets confirmed the precision of the PSInSAR™ technique for the detection and estimation of surface displacement phenomena.

It should also be noted that the positive result of the comparison gave evidence to the accuracy and reliability of the satellite data, not only for monitoring slow and constant-velocity movements, but even in cases characterised by small absolute displacements with abrupt changes and significant variations in average velocity values.

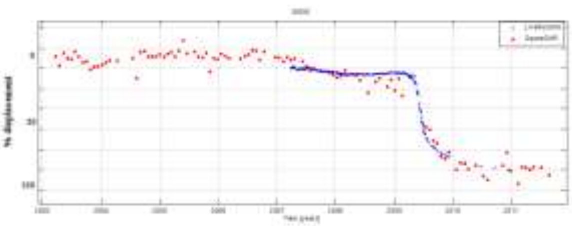

Figure 6. Comparison between the satellite data (red points) and the traditional topographic data (blue points).

In September 2001, during the excavation of the Scianina-Tracoccia tunnel for the Palermo-Messina railway line, a landslide occurred on the North slope of the hill near the village of Tracoccia. The tunnel excavation section on the Messina side (about 156m) was completely destroyed, together with part of the tunnel opening.

The landslide created an escarpment exceeding 20m in height and caused a percolation leak from the RSU dump. The roadway tunnels crossing the hill area upstream of the railway tunnel were not affected by the landslide phenomenon.

Tunnel safety and restoration required the slope to be re-stabilised with re-profiling intervention consisting of the construction of an embankment of about 60m height. The tunnel was then reconstructed according to the original layout, by carrying out significant consolidation treatments.

After the landslide, an accurate monitoring system aiming at monitoring the status of the slope and the safety of pre-existing structures was proposed.

Given the complexity of the context in which the tunnel was constructed, it was suggested to continue the monitoring activities of the structural stability of the slopes for a further three years after the completion date, in accordance with recent Italian regulations (DM 1411/2008).

The monitoring plan included not only the usual control of the deep displacements by means of geotechnical instruments, but also surface displacement monitoring by means of satellite data. There were no natural reflectors on the slopes; consequently, a network of PS ‘artificial reflectors’ was installed (Fig. 7). The artificial reflectors were constructed and installed in such a way to be seen by the satellite in both ascending and descending acquisition geometries. This reflector typology (patent pending) guarantees that the phase ‘centre’, visible from the satellite in both the acquisition geometries, is represented by the same physical point. An artificial reflector doesn't require any supply or maintenance activities and can be used, if considered necessary, even for long periods. The activities of acquisition and processing of the satellite data are in progress.

Figure 7. Monitoring phase: View of an artificial reflector installed on the slope of Tracoccia, Sicily.

4 APPLICATION FOR STRUCTURAL DAMAGE ASSESSMENT

Several types of devices are available to measure building settlement; each one differs in surveying mode, measuring precision, and cost.

New monitoring techniques can now be combined with traditional ones, allowing not only local damage phenomena to be detected, but even large scale surveying, taking into account wide area displacement. The application of traditional and advanced techniques, applied to the same building, can provide a complete monitoring system.

Traditional monitoring techniques can measure the opening of a single crack or the displacement of a single point independently from all the others and the designer is in charge for the analysis of the overall behaviour of a building. Results must be correlated whilst identifying the most probable reason for movement within the structure.

In the last 20 years, satellite remote sensing has become more and more used as a surveying technique, thanks to its capability of monitoring wide areas remotely, high precision and moderate costs.

The PSInSAR™ technique, and its recent evolution SqueeSAR™, have made it possible to monitor urban areas, by measuring the displacement of radar target with high precision.

One of the advantages of this technique is the large volume number data that satellites have already collected since the nineties. Thus, displacement time-series of identified radar targets can be used to understand historic ground deformation, even down to small structures such as building roofs.

Thanks to these characteristics, satellite remote sensing has been adopted, along with traditional surveying techniques, as a monitoring technique to measure building displacement.

Some relevant applications of the SqueeSAR™ technique used for the assessment of structural damage are given below, highlighting the advantages of radar remote sensing in structural diagnosis.

Displacement monitoring in the city of Rovigo (Italy) is one of the first applications of the PSInSAR™ technique (Jurina 2003, Jurina et al. 2003). In 2002, during a forensic case, many historical buildings in the centre of Rovigo were declared to suffer from a significant and concerning structural crack patterns. All the cracks occurred simultaneously in 1994 within the period of a few months, eight years before any forensic analysis had been conducted. Research showed that during that period an underground car park was built not far from the damaged buildings (Fig. 10). During the 10-meter high excavation the aquifer was intercepted and the groundwater level was drawn down, for a period of months.

The real difficulty was to “measure” the settlement that had occurred eight years before, and to demonstrate that the structural damage was the consequence of the parking excavation.

PSInSAR™ provided data on the ground displacement, together with the historical time-series related to the city of Rovigo, and data from the area surrounding the damaged building. Monitoring the area showed strong displacements (in the order of some centimetres) next to the parking excavation, involving an area of about 80 x 200m (Fig.11). These displacements could not be caused by the seasonal variation of the aquifer level, nor by the global subsidence phenomenon of Rovigo.

Satellite technology, integrated with geotechnical and geological investigations, could confirm that all displacements and structural damage was due to the incorrect execution of ground works. This proof was accepted during the forensic analysis.

Figure 8. “Rotonda” church in Rovigo.

Figure 9. “Cristo” church in Rovigo – structural damage to the vaults.

Figure 10. Excavation during the construction of the parking lot.

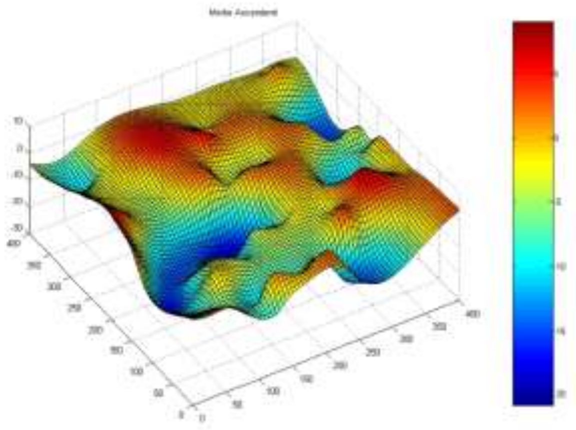

Figure 11. Settlement [mm] represented in a 3D surface diagram

A second case deals with the collapse of a marble stair in a masonry building in the centre of Milan (Fig. 12). In 2008 some excavation work was in progress to build an underground parking lot in the square in front of the building. The connection between the excavation and the collapse was supported by the evidence of strong vibrations a few days before the collapse itself, that accelerated the structural damage.

During the forensic analysis, ground displacements were “a posteriori” measured with PSInSAR™ along the entire period of construction of the parking lot in order to demonstrate the cause of the damage. Results have shown strong differential displacements of the principal facade versus the rest of the building, far from the excavation (Fig. 13).

The settlement caused an increase in internal strain in the masonry and the opening of some cracks, inducing the collapse of the brittle stairs.

Even in this case, the monitoring SAR system allowed information to be obtained about past ground movement, through the overall continuous monitoring of the displacements in different parts of the building.

Figure 12. Stair collapse in a masonry building in Milan

Figure 13. PSInSAR™ analysis over Milan. Time range 2003-2009. PS/DS Average velocity [mm/yr] along satellite line of sight

A third case has been recently proposed regarding the lake front of Como (Fig. 13). As a result of seasonal flooding of the lake, the municipality has designed some devices to regulate the lake level in order to mitigate the problem. As many historical and vulnerable buildings overlook the area, it was decided to employ both static and dynamic monitoring techniques. The SqueeSAR™ technique was applied as a necessary “safety tool”, as it can monitor a medium-scale area at regular temporal intervals. It was decided to monitor not only the front lake zone, but also the entire area exposed to hydro-geological risk.

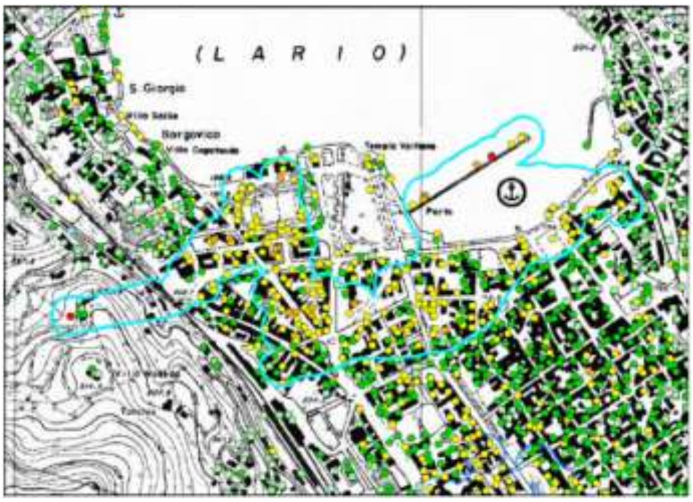

Figure 13. Como lake. SqueeSAR™ analysis performed over the area exposed to hydro-geological risk.

5 CONCLUSIONS

Thanks to its high precision and to the availability of satellite data archives covering two decades, SqueeSAR™ represents one of the most powerful techniques capable of retrieving surface displacements.

The capability of SqueeSAR to remotely monitor areas much wider than traditional surveying techniques, without the necessity to install in-situ ground instrumentation, makes this technique particularly suitable for the structural damage assessment.

Moreover the processing of archive satellite data allowed additional assessment of deformational behaviour *ante operam* (i.e. *before* the start of tunnelling activities), and therefore independent of any construction work.

The case studies described in this paper show that this kind of data may become extremely useful in the entire life cycle of a structure or infrastructure.

From a technical point of view, this instrument is ready to be used as a valuable tool for the monitoring of excavation works, historical building maintenance and settlement phenomena in urban areas.

PSInSAR™ data cannot be used as a real-time monitoring tool due to the current revisiting times of the satellites (maximum 4 days). However, considering the growing investments of the national and international community in new satellite radar sensors, it is reasonable to assume that in the near future there will be systems offering daily acquisitions. In any case, it is already an extremely useful tool which can complement conventional monitoring data.

REFERENCES

Bell J. W., Amelung F., Ferretti A., Bianchi M., Novali F. 2008. Permanent Scatterer InSAR reveals seasonal and long-term acquifer system response to groundwater pumping and artificial rechange. Water Resources Research, Vol. 44, February 2008, pages 1-18.

Bonsignore F. 2007.Il monitoraggio della subsidenza a scala regionale in Emilia Romagna. Atti del Convegno ARPA Bologna 3 dicembre 2007

Burgmann R., Hilley G., Ferretti A., Novali F. 2006. Resolving vertical tectonics in the San Francisco Bay Area from permanent scatterer InSAR and GPS analysis. Geology, March 2006, Volume 34, N. 3, pp. 221-224

Carminati E. & Martinelli G. 2002. Subsidence rates in the Po Plain, Northern Italy: the relative impact of natural and anthropic causation *Engineering Geology*. 66: 241-255 2002Colesanti C., Ferretti A., Locatelli R., Novali F., Savio G. 2003. Permanent Scatterers: Precision Assessment and Multi-platform Analysis. IGARSS 2003, 21-25 July, Toulouse, France. pp 1-3.

Colesanti C., Ferretti A., Prati C., Rocca F. 2003. Monitoring Landslides and Tectonic Motions with the Permanent Scatterers Technique. Engineering Geology, N. 68, 2003; pages 3-14

Colesanti C., Ferretti A., Novali F., Prati C., Rocca F. 2003. SAR Monitoring of Progressive and Seasonal Ground Deformation Using the Permanent Scatterers Technique. IEEE Transactions on Geoscience and Remote Sensing, Vol. 41, N. 7, July 2003; pages 1685-1701

Dixon T., Amelung F., Ferretti A., Novali F., Rocca F., Dokka R., Sella G., Kim S., Wdowinski S., Whitman D. 2006. Subsidence and Flooding in New Orleans. Nature, Vol. 441, June 2006

Ferretti A., Prati C., Rocca F. 2001. Permanent Scatterers in SAR Interferometry. IEEE Transactions on Geoscience and Remote Sensing, Vol. 39, NO. 1, January 2001, Pages 8 – 20

Ferretti A., Colesanti C., Prati C., Rocca F. 2001. Comparing GPS, Optical Levelling and Permanent Scatterers. Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, IGAARS 2001, Sydney (Australia), 9-13 July 2001, VOL. 6, Pages 2622-2624, 2001

Ferretti A., Fumagalli A., Novali F., Prati C., Rocca F., Rucci A. 2010. A new algorithm for processing interferometric data-stacks: SqueeSAR™. Submitted to IEEE Trans. on Geoscience and Remote Sensing, November 2010

Hilley G., Bürgmann R., Ferretti A., Novali F., Rocca F. 2004. Dynamics of Slow-Moving Landslides from Permanent Scatterer. Analysis, Science, Vol. 304, 25 June 2004 Volume 304, Number 5679, Pages 1952-1955

Jurina L, Ferretti A, Franchioni G. 2003. Valutazione degli effetti di scavi in falda sui cedimenti strutturali di edifici mediante utilizzo di tecniche satellitari SAR. Convegno Internazionale “Crolli e stabilità delle strutture”, Università di Napoli

Jurina L. 2003. Tecniche satellitari SAR. L’analisi “a posteriori” dell’entita’ dei cedimenti negli edifici. L’edilizia , n. 129, pp 72-75,

Jurina L., Ferretti A. 2007. Permanent Scatterers technology: a powerful tool for historic and future monitoring of building and landslides settlements, Conferencias Intercon 2007, Piura (Cile) 7-10 agosto

Klemm H., Quseimi I., Novali F., Ferretti A., Tamburini A. 2010. Monitoring Horizontal and Vertical Surface Deformation over a Hydrocarbon Reservoir by PSInSAR™. First Break, Vol. 28, 2010

Massonnet, D. & Feigl, K. L. 1998, Radar interferometry and its application to changes in the Earth's surface, Reviews of Geophysics., 36(4), 441–500.

Pigorini A., Ricci M., Sciotti A., Giannico C., Tamburini A. 2010. La tecnica PSInSAR™ di telerilevamento satellitare applicata al progetto ed alla realizzazione delle infrastrutture ferroviarie. Ingegneria Ferroviaria anno LXV Ottobre 2010 (10) pag 729

Ringrose P., Atbi M., Mason D., Espinassous M., Myhrer O., Iding M., Mathieson A., Wright I. 2009. Plume Development Around Well KB-502 at the In Salah CO2 Storage Site. First Break , Vol. 27, 2009