PS InSAR Integrated with Geotechnical GIS: Some Examples from Southern Lombardia

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Abstract. The Oltrepo Pavese, which extends for almost 1100 km^2 in Lombardia Region (Northern Italy), has a complex geological-structural setting resulting from overthrusting of different tectonic units made up mainly of clays. All these characteristics make the Oltrepo Pavese particularly vulnerable to hydrogeological risk: shallow and deep landslides in the hill, swelling/shrinkage of the clayey soils and subsidence in the plain. In order to understand more about the hydrogeological hazard (related to landslides and other phenomena) and related risk in the Oltrepo Pavese area the Regione Lombardia decided to test the use of the Permanent Scatterers Technique.

The Permanent Scatterers (PS) Technique is an advanced technique for the processing of SAR data developed by Politecnico of Milano. The PS Technique overcomes the main limits of conventional approaches to surface deformation detection due to temporal and geometric decorrelation.

The PS data sets and their temporal series were included on a geological and geotechnical GIS supported data-base, where they were integrated with geological-structural, hydrogeological and geomorphologic data. Spatial and temporal clusters were highlighted and/or discovered. They are generally related to ground deformation due to well known phenomena (swelling/shrinkage, landslides, overpumping) or to unknown phenomena (uplift).

Keywords. InSAR, GIS, landslides, subsidence.

1 Introduction

Differential Synthetic Aperture Radar Interferometry (DInSAR) allows the measure of very small movements of the ground over time and large area coverage (100x100km for ERS data). However, DInSAR suffers for temporal and geometric decorrelation. The Permanent Scatterers technique developed by Politecnico of Milano (Ferretti et al. 2001) overcomes the main limitations of conventional DInSAR approaches. It identifies, quantifies and removed atmospheric distortions, leaving displacement as the only contribution to signal phase shift. DInSAR and particularly PS technique are powerful techniques for geological risk assessment and monitoring (e.g. landslides, subsidence, earthquakes) (Ferretti at al. 2000; Crosetto et al. 2002; Berardino et al. 2003; Colesanti at al. 2003; Canuti et al. 2004). Such an approach provides fast and updatable data acquisition over large areas, which can integrate conventional methods (e.g. field surveys, aerial photointerpretation). Of particular interest is the possibility to combine deformation measurements with geological data in a Geographical Information Systems.

The paper presents an application of the Permanent Scatterers technique for detecting and monitoring ground displacement related to landslides and other phenomena in the Oltrepo Pavese, which could be considered representative, in terms of geological hazard, of the Italian Apennines.

2 Study Area

2.1. Geological and geomorphological settings

The Oltrepo Pavese, which is situated in Northern Italy (Southern Lombardia), has an extension of about 1100 km^2.

Its Southern part corresponds to the northwestern sector of the Apennines. The area is at heights between 200 m and 1725 m a.s.l. and it is characterized by a complex geological and structural setting.

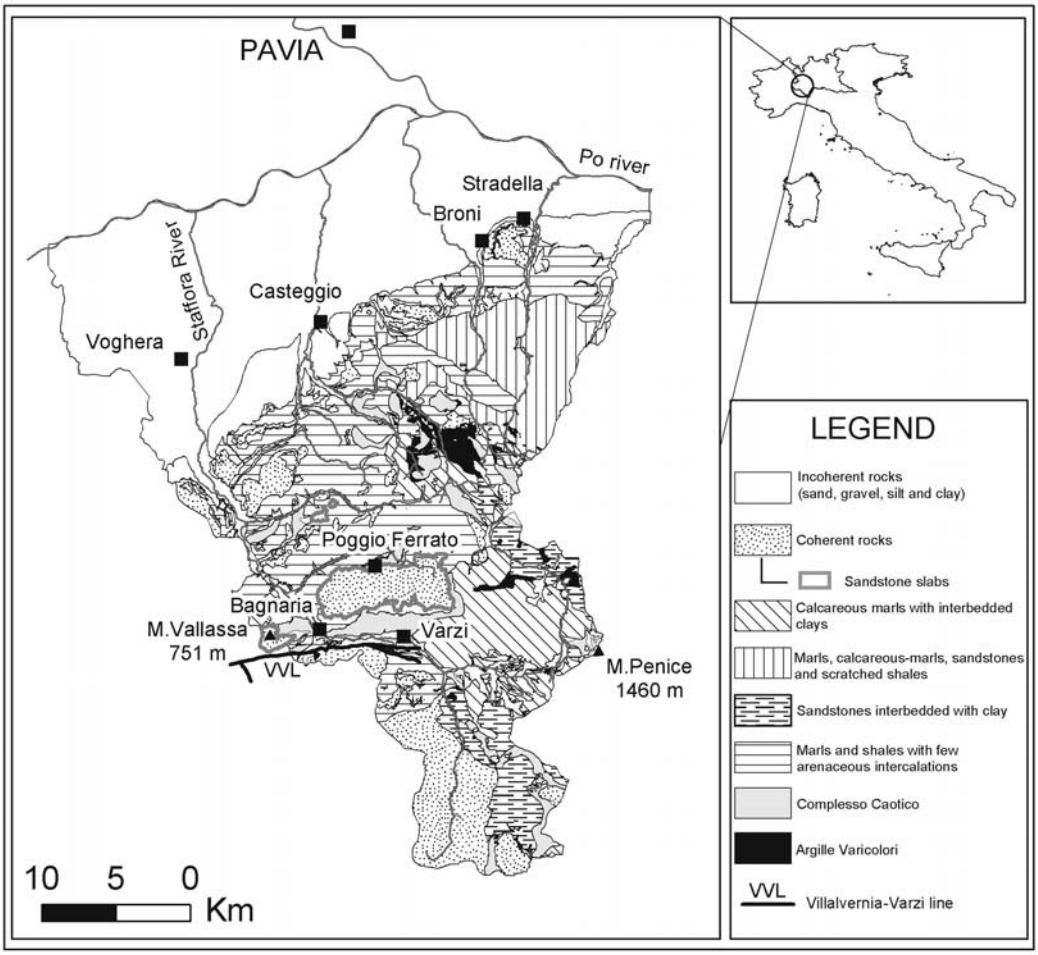

Fig. 1 Lithological map of the study area.

The geology is dominated by sedimentary formations, with a dominant clay component (Beatrizzotti et al. 1969; Braga et al. 1985) (Fig. 1). Clay shales, referred to as Argille Varicolori (varicoloured clays), or Complesso Caotico (chaotic complex), outcrop throughout the Oltrepo Pavese area, while calcareous flysch, made up of alternating marl, calcareous marl, and scratched shale predominated in the eastern part. Sandstones slabs lying on a deformable clayey substratum, are present as isolated area of relief in the central part. Silty and/or clayey deposits formed by weathering and down slope transportation cover the argillaceous bedrock units.

The northern part of Oltrepo Pavese corresponds to the Po River Plain. Morphologically, fluvial terraces and piedmont alluvial fans characterise this part. The recent river deposits consist of mainly coarse grained units. All along the piedmont margin, which separates the first foothills of the Apennines from the alluvial deposits of the Po plain, three orders of fluvial terraces deposits are present. The upper part of the older alluvial deposits is strongly weathered and it is composed of a large amount of clay.

The climate of Oltrepo Pavese has an average annual rainfall of around 700 mm in the plain and 998 mm in the hills. There are two distinct rainy seasons with the maxima in May and in October-November (Rossetti and Ottone 1979). The region has experienced, in the last two decades, many drought periods. The last major droughts were March 1989 - August 1993 (the most severe drought of the period) and May 1998 – September 2000.

2.2. Geological hazards

The main geological hazards are represented by landslides and subsidence due to shrinkage of clayey soils or ground water pumping.

The Oltrepo Pavese is characterized for the presence of a high number of mass movements, which cover up to 40% of the territory in the north-eastern sector. Up today 3707 landslide were mapped, the 89 % of which are active or dormant. A lot of them have been classified at high risk from the institutional authorities. The most frequent typologies are roto-translational slides associated with complex earth slides/earth flows. Most of the active landslides are relative small shallow landslides affecting the surficial cover, whereas dormant and inactive landslides are mainly slides or complex failures.

Swelling/shrinking soils occur extensively throughout the Oltrepo Pavese. The material source of expansive/shrinking soils is from the weathering of the sedimentary rocks in the hills and the alluvial deposits in the Apennine fringe and Po River Plain (Meisina, 2003).

A large number of residential buildings (more than 1000) have experienced damages. The majority of problems are related to single storey family residences. The buildings are founded on conventional concrete shallow strip footings, which generally extend to depths of between 1 m and 2 m below ground level. For the 46 % the causes the damages are due to landslide, for the 20 % the cause is the volume change of clay soils. The economic losses due to volume changes of clay soils have been estimated at around 20% of the building cost.

In this context the Lombardia government decided to test how PS technique may help to detect and to monitor geological hazard for risk assessment.

3 Methods

The project focuses on the combination of the PS analysis, able to provide displacement measurements on sparse points with geological and geotechnical data by the way of GIS.

3.1. Permanents Scatterers Technique

The Permanent Scatterers (PS) Technique is an advanced algorithm for the processing of data acquired by SAR sensors developed by Politecnico of Milano (Ferretti et al. 2001). It is an operational tool for ground deformation mapping at millimetric level on a high spatial density grid of phase stable radar targets (the so-called Permanent Scatterers, PS), acting as a "natural" geodetic network. In the Oltrepo Pavese the PS mainly correspond to man-made structures such as buildings. The PS approach allows to overcome the two most significant drawbacks of conventional Differential SAR Interferometry (DInSAR), namely decorrelation noise and atmospheric artifacts. The PS technique was already used to detect and monitor different geological phenomena such as: subsidence, landslides, seismic faults etc. and even to verify individual building stability (Ferretti et al. 2000; Colesanti et al. 2003; Farina et al. 2005).

Seventy-six ESA ERS1 and ERS2 images gathered along descending orbits and 26 images gathered along ascending orbits in the time span May 1992- November 2000/December 2001 have been exploited in Oltrepo Pavese. The analysis resulted in the identification of around 95500 descending PS and 3800 ascending PS. The minor number of ascending PS is due to the limited number of the images acquired along ascending orbit.

The most part of PS is in the plain area of Oltrepo Pavese, where density of man-made structures is the highest. No PS were detected in the mountain part of the area (the southern part) due to the limited number of urban areas and to the vegetation cover.

The LOS (Line of sight direction) displacement rates vary from +5 to -5 mm/yr.

Two type of PS analyses were performed: Standard Permanent Scatterers Analysis and Advanced Analysis. The Standard Permanent Scatterers Analysis (hereinafter SPSA) is suitable for mapping the territory at regional scale, in order to identify unstable areas, which deserve further detailed studies. PS are detected and their average velocity is then estimated by an automatic procedure, allowing to process large amounts of data relative to large areas in a limited period of time. Linear motion model is searched and information about linear velocity is extracted.

The Advanced Analysis (hereinafter APSA) is suitable for those small areas where a full exploitation of the information content of the satellite data is required. It is a very sophisticated and time-consuming analysis, which requires skilled technical staff. With the APSA the nonlinear movements can be estimated.

3.2 Geological and geotechnical databases

On the whole territory a standard PS analysis was performed and only the descending PS dataset was taken into account. The Permanent Scatterers interferometric analysis was integrated in a GIS with the geology (lithology and geostructures), the landslide and damaged building databases.

The landslide database consists in a landslide inventory produced from 1994 aerial photographs analysis supported by field checks. Mass movements were classified in relationship with their state of activity (active, dormant, inactive) and typology.

The damaged buildings database contains information concerning the type of soil foundation, the type of damage and the remedial works.

The SPSA analysis aimed to identify the general clusters of the ground movement in the area (uplift or subsidence), to verify or update the state of activity of the landslides, to update the landslide inventory with the identification of new unstable area and to verify the relationship between the PS and the damaged buildings.

Four significant test sites were selected and the APSA analysis was applied to. A geological model of each test area was obtained from the integration of the geological-geomorphological character of the site with the geotechnical data (penetrometer tests, boreholes and laboratory tests). The rainfall deficit, obtained by the arithmetic difference between the monthly water balance (difference between precipitation and potential evapotranspiration) and the average monthly water balance calculated over a 40-year-period, was studied. The ground water table fluctuations and the ground water pumping were also analysed and compared with the time series of the PS displacement occurring along the sensor-target line of sight (LOS) direction.

4 Results

4.1 General analysis

In the plain two areas of ground subsidence were clearly identified in the towns of Voghera and Broni (510 and 986 PS/km^2 respectively). In the first case the ground movement of the eastern part of Voghera was until now unknown. The subsidence of 10-30 mm from 1992 to 2000 (1-3 mm/yr) could be related to the presence in the subsoil of clay deposits thicker than 6-7 m. In the town of Broni clay shrinkage phenomena were already known and they are the cause of a lot of damage to buildings. The SPSA analysis detects a ground subsidence in the north-eastern part of about 10-22 mm from 1992 to 2000 (1-5 mm/yr).

Two areas of uplift were identified in the towns of Casteggio and Varzi (397 and 136 PS/km^2 respectively). In the Casteggio area the heave (1.3 mm/yr) could be related with the uplift of the miocenic substratum observed by geophysical prospecting (Pieri and Groppi, 1981). The SAR data are also in agreement with topographical measures of IGM (Italian Militar Geographic Institute) that registered a vertical movement in the same area (Arca and Beretta, 1985), even if with lower velocity (0.5 mm/yr for the time span 1897-1957).

In the Varzi zone the uplift (3 mm/yr) was also identified with the study of the alluvial sediment thickness along the Staffora riverbed. Between Bagnaria and Varzi the Staffora river is parallel to Villavernia-Varzi Line (VVL), defined as a dextral transpressive system, that constitutes one of the most important structural elements in the North Western Apennines (Cerrina Feroni et al. 2002) (Fig.1). The VVL divides the Staffora River, into two blocks: the northern block (downstream Bagnaria) with the minimum alluvial sediment thickness and the southern block (upstream Bagnaria) with the higher values of thickness. The different thickness of the alluvial sediments could be related to an uplifting of the northern block followed by the erosion of the alluvial sediments (rejuvenation process) (Piccio and Meisina, 2003). This is also in agreement with the soil vertical movement map of Arca and Beretta (1985).

The compliance analysis of the PS data sets and landslides in terms of distribution and state of activity allows to verify that the 7% of the descending PS are located on landslides (Fig.2). The great majority of moving PS fall within landslides classified as inactive from the geomorphological point of view. The PS analysis allows to modify the state of activity of 16 landslides (from inactive to active). A limited number of unstable areas not yet mapped have been detected through the use of the PS.

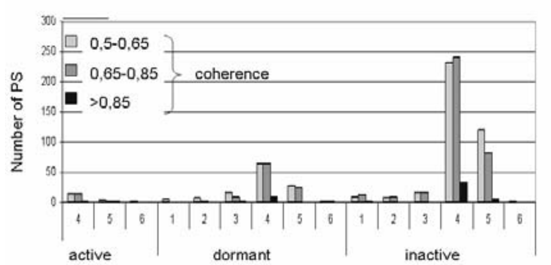

Fig.2 PS distribution vs landslide activity. Velocity classes 1: < -5 mm/yr, 2: -3/-5 mm/yr, 3: -1/-3 mm/yr, 4: -1/+1 mm/yr; 5: +1/+3 mm/yr; 6: +3/+5 mm/yr; 7: > +5 mm/yr.

Strong subsidence phenomena (-11 mm/yr) were detected on isolated area of relief, consisting of sandstones slabs lying on a deformable clayey substratum. This phenomenon develops on the borders where the slabs are highly fractured, with more sets of subvertical joints which separate sandstones blocks.

The PS distribution was also compared with the damaged building inventory. The 33 % of the damaged buildings are Permanent Scatterers. The PS velocity (<-1 mm/yr or > +1 mm/yr) allowed the confirmation of damage for the 20% of these buildings in the plain and the 40% in the hill. The damaged buildings with "stable" PS (velocity between +1 and –1 mm/yr) correspond to repaired houses before or within the monitored period. New unstable buildings not yet mapped were also detected on the basis of PS velocity (<-1 mm/yr or > +1 mm/yr).

4.2 Detailed analysis

Two examples of application of the APSA are presented in this section of the paper; they concern the Poggio Ferrato landslide and the town of Broni.

The landslide of Poggio Ferrato is located on the external northern border of a sandstone slab lying on a clay substratum (Fig.1 and 3). The landslide, is classified as an active complex failure: the movement started as a roto-translational slide with a NE-SW direction and became an earth flow with a NNW-SSE direction (Fig.3A). It has an elongated morphology with lengths of a thousand meters. In the last 50 years the crown has retrogressed by 250 m. In the same period the flow advanced about 855 m. A serious increase in the movements was recorded in December 1996, after a long period of heavy rainfall. The channel keeps on moving with displacement rates of 10 m/day and the flow advances about 160 m which caused cracks to open in nine buildings in the northern part of the village of Poggio Ferrato.

Site investigation consisted of 16 boreholes from 9 m to 40 m, trench pits and geophysical surveys. A geological model of the site was derived. The boreholes have found different thicknesses of the Sandstones (from 7 to 30 m) around Poggio Ferrato village (Fig.4). This has been explained by the existence of an important structural discontinuity, dipping SW and subvertical, which indicates differential settlement and sinking of sandstone blocks on the border of the slab (Fig. 3B and 4). Most of the damaged buildings are located near the outcrop of this discontinuity. The structural and geomorphological surveys and comparison with results obtained by some authors in similar geological contexts (Conti and Tosatti 1994) indicate the presence of deep-seated gravitational deformations, which could be classified as lateral spreads and block type slope movement (Braga et al. 2003). The stability conditions of the slope are governed by the groundwater circulating in the sandstone, sustained by the impermeable clayey and marly substratum. The waters emerging at the ground surface and flowing down the hill cause the softening of the clayey soils and contribute to the progress of slope movements.

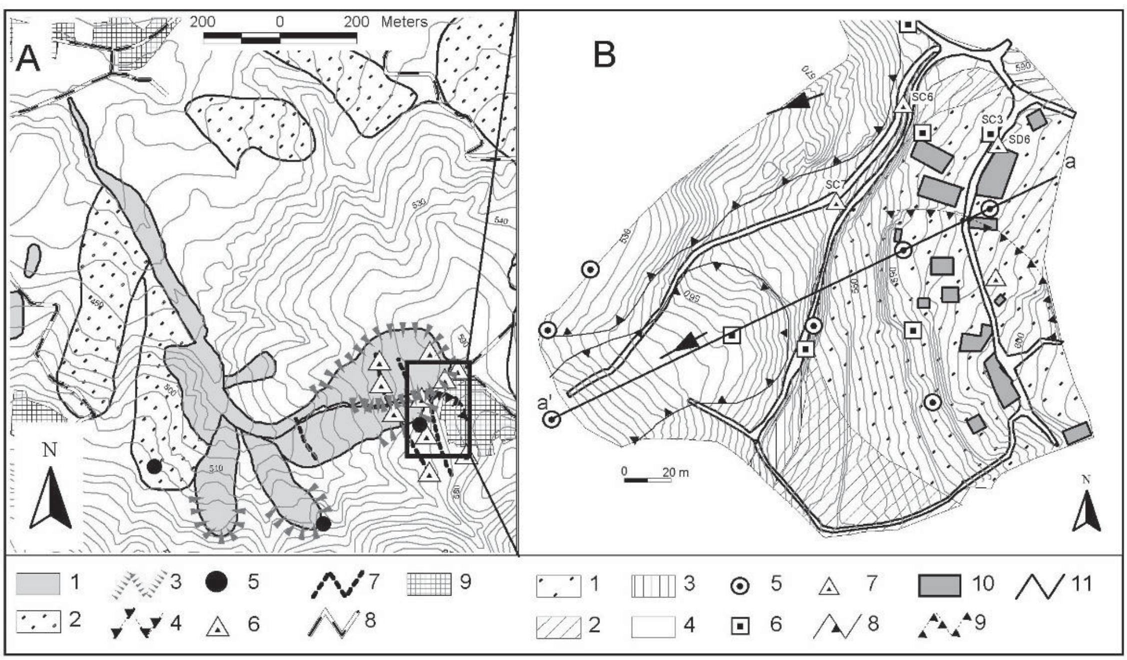

Fig.3 A: The active Poggio Ferrato landslide. 1: active landslide; 2: dormant landslide; 3: landslide scarp; 4: fracture; 5: spring; 6: trench pit; 7: seismic refraction profile; 8: road; 9: urban area. B. Detail of the old villane of Poggio Ferrato. 1: M. Vallassa Sandstone; 2: Monte Lumello Marls; 3: M. Piano Marls; 4: Chaotic Complex; 5: borehole; 6: borehole + open pipe piezometer; 7: borehole + Casagrande piezometer; 8: landslide scarp; 9: fracture; 10: building; 11: line of the geological sections.

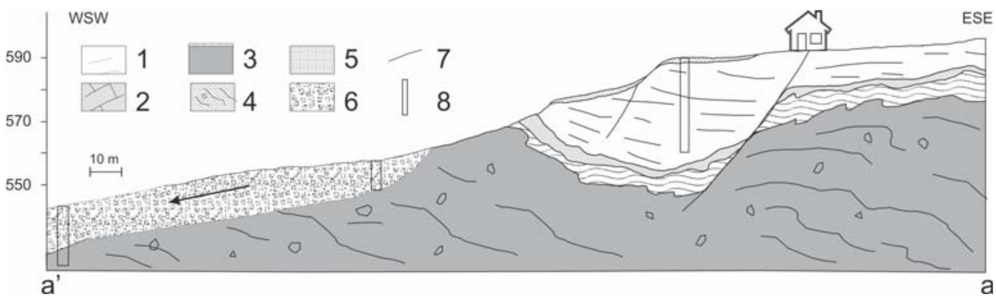

Fig.4 Longitudinal section of the depletion zone of the Poggio Ferrato landslide. 1: M. Vallassa Sandstone; 2: Monte Lumello Marls; 3: M. Piano Marls; 4: Chaotic Complex; 5: weathered sandstone; 6: landslide; 7: fracture; 8: borehole.

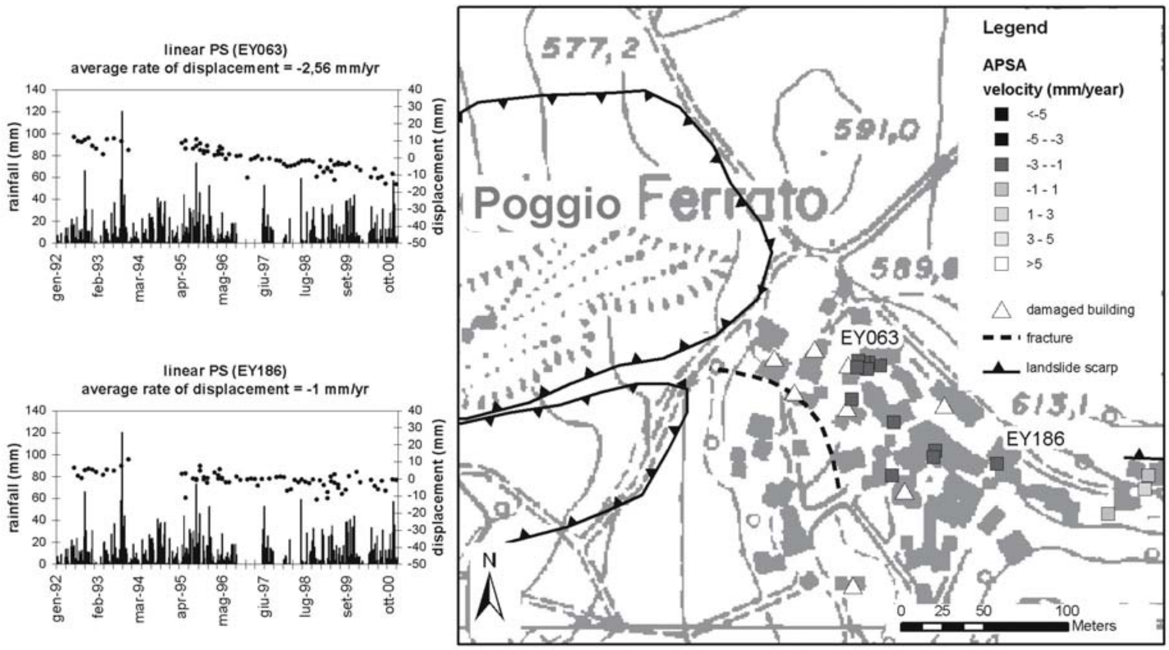

Fig.5 Aerial photo of the Poggio Ferrato landslide showing the distribution of the Permanent Scatterers.

The results of the advanced PS analysis are shown in Figure 5. A limited number of linear PS were obtained. The PS analysis shows a significant settlement of the sandstone slab in correspondence of the old village (25-35 mm in the period 1992-2000). The PS velocity ranges between –1 (southern part of the village) and –3 mm/year (north-eastern part). The SAR data support the geological hypothesis of a differential settlement and sinking of sandstone blocks on the border of the slab near Poggio Ferrato. The lack of PS in the north-western part of the village, that is the nearest to the landslide crown and where are concentrated the larger number of damaged buildings, could be related to the magnitude of the ground displacements, probably greater than 2.8 cm, which is the maximum displacement between two consecutive acquisitions. The historical series shows that the settlement is continuous in the period, there are not abrupt changes in correspondence of the reactivation of the landslide after December 1996.

The town of Broni, located in the Apennine fringe, is build upon alluvial fan deposits, which are very heterogeneous. A geological model of the area was obtained from the integration of the geological-geomorphological characteristics of the site with the geotechnical data (penetrometer tests, boreholes and laboratory tests). Silty clay and clayey silty deposits of high to very high swelling/shrinking potential constitute the first layer. They are soft soils with a tip resistence, measured with cone penetrometer test, of 1-2 MPa and their thickness varies from 4 m in the western part to 20 m in the northeastern. In the western sector thin lens of silt and sand are interbedded. The underlying layers consist, from top to bottom, of sand and gravel, silty clay, gravel and Tertiary marls.

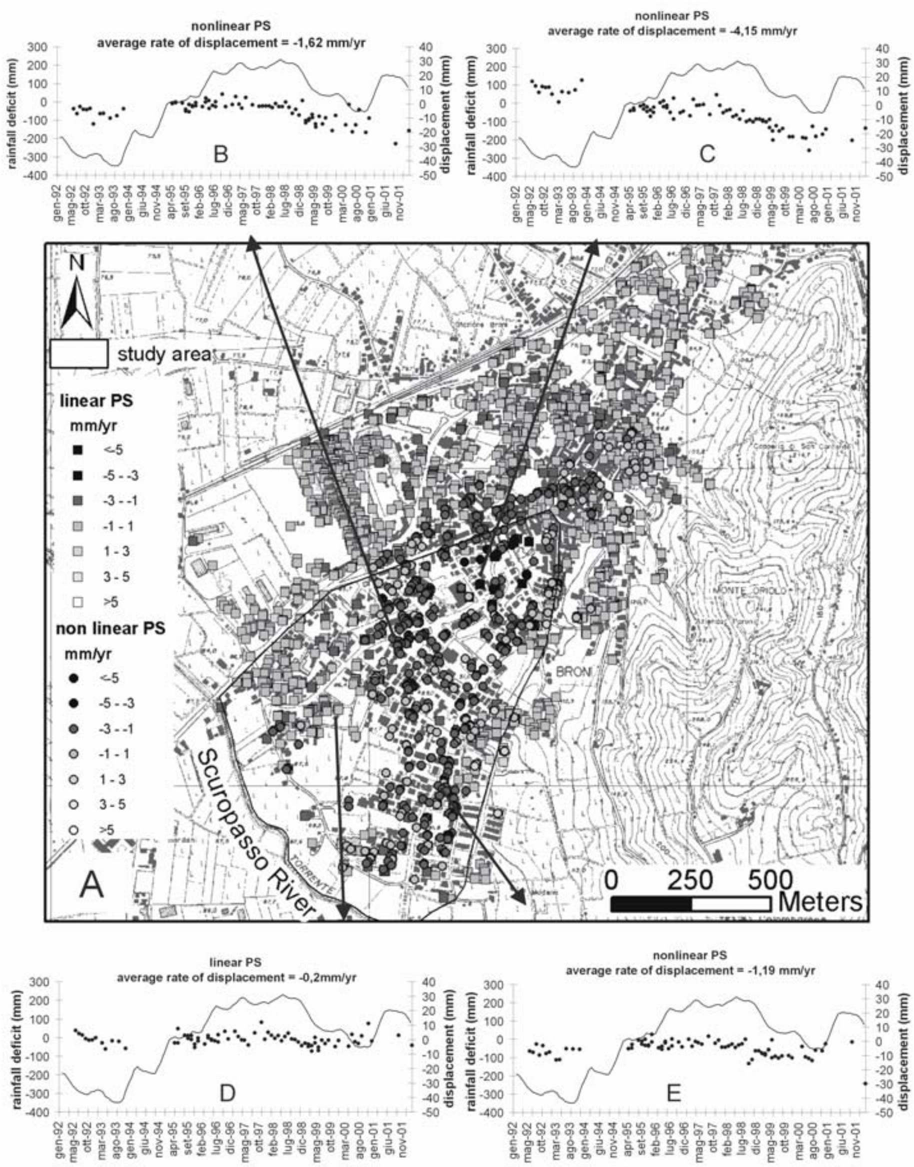

Fig.6 A: Linear and non linear advanced Permanent Scatterers. B, C, D, E: Time series relative to different Permanent Scatterers.

The alluvial deposits consist of two aquifers interbedded with discontinuous silty clay aquitard: the groundwater is pumped from the deepest, which is a semi-confined aquifer with a depth from 10 to 25 m. The water table fluctuation in drought period reaches 2.5-3 m. The depth of the active zone in the period 1992-2000 was 2.8 m. The moisture regime of soil could also be influenced by a seasonal perched water table.

Several buildings (single storey family residences), founded on conventional concrete shallow strip footings, were damaged in the last years; the cracks appeared at the end of 1980s (drought period) with a worsening in 1998-2000. Cracks are progressive and generally close up during the wet season in relationship with rainfall and open up again during the dry seasons.

The ASPA identifies vertical ground displacement in the northern and in the eastern part of Broni near the Apennine fringe, where nonlinear PS are present (Fig.6). This is in agreement with the soil stratification and clay thickness. The time series of nonlinear PS show abrupt variations after May 1998: we observe a rapid increase of the settlement that reaches 14-22 mm at the end of the drought period. The comparison between the vertical displacement of the Permanent Scatterers and the rainfall deficit curves shows a relationship between the curves. The phenomenon could be related to the shrinkage of the soil in the drought period. The lowering of the water table associated with pumping well could contribute to the ground settlement.

5 Conclusions

InSAR for the wide area coverage (100 x 100 km), the high spatial resolution (20 x 20 m) and the availability of a long historical SAR dataset (more than 14 years) may used as powerful instruments for monitoring and detection of surficial deformations. Its intrinsic limits due to temporal and geometric decorrelation may be overcame by the use of some techniques of persistent scatterers analysis as the Permanent Scatterers of Ferretti et al (2000-2001).

In this study the PS analysis at a large scale (SPSA) allows to verify the existence of known unstable areas (buildings, landslides and shrinkage phenomena) and to identify unknown phenomena (subsidence on the border of the sandstone slabs, new unstable areas, uplift zones, new damaged buildings). Discrepancies between the PS distribution/velocity and the landslides movements were also identified and allowed the modification of the state of activity of some landslides.

The PS analysis at detailed scale (APSA) allows to study the temporal evolution of the phenomena also of non-linear type.

The PS also allowed the production of deformation rate maps (e.g shrinkage in drought period) for the derivation of qualitative hazard zonation very useful for land planning.

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