Ground deformation monitoring by using the Permanent Scatterers Technique: The example of the Oltrepo Pavese (Lombardia, Italy)

C. Meisina a,⁎, F. Zucca a, D. Fossatib, M. Cerianic, J. Allievid

a Department of Earth Sciences, University of Pavia, Via Ferrata no. 1, 27100 Pavia, Italy
b Regione Lombardia-Struttura Rischi Idrogeologici, Milano, Italy
c Regione Lombardia, D.G. Polizia Locale, Prevenzione e Protezione Civile, Milano, Italy
d Tele-Rilevamento Europa- T.R.E. S.r.l, Milano, Italy

Accepted 11 September 2006
Available online 31 October 2006

Abstract

The applicability of the Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR) technique for detecting and monitoring ground displacements was tested in the Oltrepo Pavese territory (Northern Italy, southern Lombardia), which could be representative of similar geological contexts in the Italian Apennines. The study area, which extends for almost 1100 km², is characterized by a complex geological and structural setting and the presence of clay-rich sedimentary formations. These characteristics make the Oltrepo Pavese particularly prone to several geological hazards: shallow and deep landslides, subsidence and swelling/shrinkage of the clayey soils. The PSInSAR technique used in this study overcomes most of the limitations of conventional interferometric approaches by identifying, within the area of interest, a set of “radar benchmarks” (PS), where very precise displacement measurements can be carried out. More than 90,000 PS were identified by processing Synthetic Aperture Radar (SAR) images acquired from 1992 to 2001 by the European Remote Sensing satellites (ERS). The PSInSAR application at a sub-regional scale detected slow ground deformations ranging from +5 to −16 mm/year, and resulting from various processes (landslides, swelling/shrinkage of clay soils and water pumping). The PS displacements were analysed by collecting data obtained through geological, geomorphologic field surveys, geotechnical analysis of the soils and the information was integrated within a landslide inventory and the damaged building inventory. Despite the limited number of landslide bodies with PS (7% of the inventoried landslides), the PS data helped to revise the state of activity of several landslides. Furthermore, some previously unknown unstable slopes were detected. Two areas of uplift and two areas of subsidence were identified.

© 2006 Elsevier B.V. All rights reserved.

Keywords: SAR interferometry; Permanent Scatterers; Landslide; Swelling/shrinkage; Oltrepo Pavese

1. Introduction

Because of its wide area coverage (100 × 100 km for ERS data), high spatial resolution (20 × 20 m) and the availability of a long historical SAR data set, differential synthetic aperture radar interferometry (DInSAR) can be a powerful method to monitor and detect surface deformations (Gabriel et al., 1989; Crosetto et al., 2002; Berardino et al., 2003; Chang et al., 2004). DInSAR is based on the comparison of SAR images, acquired at different times with slightly different looking angles. Its intrinsic limits due to temporal and geometric decorrelations can be overcome by the use of the Permanent...
Scatterers interferometry technique (PSInSAR), which relies on an advanced algorithm for the processing of data acquired by SAR sensors (Ferretti et al., 2000, 2001).

PSInSAR is an operational tool for precise ground deformation mapping on a sparse grid of phase stable radar targets (the so-called Permanent Scatterers, PS), acting as a “natural” geodetic network. This technique identifies, estimates and removes atmospheric distortions, leaving the PS displacement as the only contribution to the signal phase shift. SAR data and, in particular, PSInSAR can be very useful for geological hazard assessment (e.g. landslides, subsidence, earthquakes) (e.g. Ferretti et al., 2000; Colesanti et al., 2003a,b; Canuti et al., 2004; Colesanti and Wasowski, 2004; Ferretti et al., 2005). Such an approach provides fast and updatable data acquisition over large areas, and can be integrated with conventional methods of investigation (e.g. field surveys, airphotos interpretation). Of particular interest is the possibility to combine deformation measurements with geological data in a geographical information system (GIS).

This paper presents an application of PSInSAR for detecting and monitoring ground displacements in the Oltrepo Pavese region. This area is of particular interest because of its large number of geohazards (landslides, subsidence, swelling/shrinkage of clay soils, subsidence). Moreover, this area can be considered as geologically representative of a large part of the Italian Apennines. The aims of this work are:

1. To delimit and to map areas characterised by significant Line of Sight (LOS) displacements and to examine the detected movements using the available in-situ data;
2. To investigate the potential and the limitations of the PSInSAR to detect and to monitor the different types of geohazards in the Oltrepo region.

2. Geological and geomorphological setting of the study area

The Oltrepo Pavese, which is situated in Northern Italy (Southern Lombardia), has an extension of about 1100 km². Its southern part corresponds to the northwestern sector of the Apennines. The area, with elevations between 200 m and 1725 m a.s.l., is characterized by a complex geological and structural setting.

The geology is dominated by clay-rich sedimentary formations of Cretaceous–Pliocene age (Beatrizotti et al., 1969; Braga et al., 1985). The rocks cropping out in the study area were divided into 8 lithological groups according to their composition and mechanical properties (Fig. 1). Clay shales (Varicoloured Clays) or the Chaotic Complex (blocks or fragments of more or less weathered rocks of various origin in a clayey matrix) crop out all the area, while flysch, made up of alternating marl, calcareous marl, and scaly shale is present mostly in the eastern part. Some sandstones slabs lying on a deformable clayey substratum are present as isolated caprocks in the central part. Calcareous flysch made up of alternating limestone and marls crops out in the southern part. Slopes in the argillaceous and marly successions are mantled with 1 to 6 m thick clayey–silty colluvial deposits.

The most important tectonic structure is the Villavernia-Varzi Line (VVL). The VVL, defined as a dextral transpressive system (Cerrina Feroni et al., 2002), separates two structural areas. In the south, the Tertiary Piedmont Basin (TPB) is represented by upper Eocene–lower Miocene sedimentary sequence with a synclinal structure. In the north, the Voghera Apennine is characterized by the presence of deformed sedimentary sequences of lower Cretaceous to Pliocene age.

The geomorphological setting of the area is controlled by the geological and structural conditions and the landscape evolution is essentially controlled by mass-movements. The slopes are in general slightly inclined (slope angles <20°); steeper slopes correspond to rock outcrops (limestone in the southern part and sandstone in the central part).

The northern sector of Oltrepo Pavese belongs to the Po River Plain. Morphologically, fluvial terraces and piedmont alluvial fans characterize this sector. The recent river deposits consist of mainly coarse-grained units. All along the piedmont margin three orders of fluvial terraces are present. The upper part of the older alluvial deposits is strongly weathered and includes a large amount of clay. In the hilly area, the main land uses are vineyards and cultivated areas. Forests cover the southern part of the area.

In Oltrepo Pavese the average annual rainfall is about 700 mm in the Po 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).

3. Geological hazards

The geological, structural and geomorphological characteristics make the Oltrepo Pavese particularly prone to geological instabilities: shallow and deep landslides, swelling/shrinkage of the clayey soils and subsidence in the Po plain.
An inventory of damaged buildings was prepared on the basis of the claims presented by the homeowners to the Lombardia Region and on the basis of several detailed field checks. The data concerning the type of soil foundation, the type of damage and the remedial works were stored in a database.

More than 1200 residential buildings have experienced damage. Single storey family residences are the mostly affected. These buildings are founded on conventional concrete shallow strip footings, between 1 m and 2 m below ground level. Landslides account for 46% of the damages and volume change in clay soils for 20%. The economic losses due to volume changes of clay soils have been estimated at around 20% of the building costs.

In this context the Lombardia government decided to test how PSInSAR may help to detect and to monitor the above geological hazards and assist in risk assessment efforts.

3.1. Landslides

The Department of Earth Sciences (University of Pavia) produced for the Province of Pavia, a 1:10,000 scale landslide inventory using 1:25,000 scale black-and-white aerial photographs, acquired in 1994. The photo-interpretation was validated through several field checks in 1999–2000, which allowed also to classify the slope movements in relation to the state of activity, following geomorphological criteria (e.g. hummocky...
of a high number of landslides (Carrara et al., 2003; Guzzetti et al., 2005), which cover 17% of the territory (up to 40% in the north-eastern sector). The most frequent types are complex (rotational and translational slides associated with earth flows) and involve: sandstones interbedded with clays, marls, calcareous marls, sandstones and scaly shales, and calcareous marls with interbedded clays. Translational slides are not very common. They are generally deep seated and large, and involve the bedrock made of marls and shales with few arenaceous intercalations. Very large rotational and translational slides are concentrated in the southern part of the study area in relation with calcareous flysch. Small rockfalls are associated with sandstone and limestone outcrops in the central and southern sectors.

Structural and geomorphological surveys indicate the presence of lateral spreads. They are present where sandstone slabs lie on a deformable argillaceous-marly substratum (Braga et al., 2003).

Shallow landslides (rotational or translational slides followed by flowage of the disturbed mass, affecting the superficial cover, are very common in the Chaotic Complex and Varicoloured Clay. These landslides are generally 20–50 m wide, 10–100 m long and 1–2 m deep. Heavy rainfall periods following dry periods, as in 1993, 1996 and 2000, have triggered such failures. These landslides have been strongly modified by farming activity and therefore are not easy to identify.

Until today, 3707 landslides have been mapped, 89% of them are active or dormant. Many of the active landslides have been classified as high risk areas, according to Italian Law. Most of the active landslides are relatively small shallow movements affecting the superficial cover, whereas dormant and inactive landslides are mainly complex failures (rotational or translational slides evolving into earth flows).

A temporal analysis of the landslide evolution was performed on five sets of aerial photographs at 1:13,000 to 1:33,000 scale relative to the period from 1954 to 2000. Generally most of the landslides were reactivated in the period 1954–1980, with a particular strong increase of the movements in the period 1976–1978, characterized by intense rainfall events. A decrease of activity (from active to dormant or inactive) was observed after the 1980s, due to low rainfall and to the great number of completed remedial works. The 1994–2000 period was characterized by small reactivations of shallow landslides in 1996–1997 and 2000.

### 3.2. Swelling–shrinkage of the clay soils

Swelling/shrinking soils are frequent throughout the Oltrepo Pavese. The material forming these soils comes from the weathering of the sedimentary rocks and the alluvial deposits.

The expansive/shrinking soils in Oltrepo Pavese can be divided into three basic types (Meisina, 2003): eluvial–colluvial soils (I), alluvial soils (II) and aeolian soils (III). The eluvial–colluvial expansive/shrinking soils (I) are distributed on the hilly areas with gentle slopes. The material source for the subtype Ia, is from the weathering of Varicoloured Clays and Chaotic Complex. Calcareous marl with interbedded clays and marls (subtype Ib), and calcareous marls, sandstones and scaly shales (subtype Ic). Volume changes are sometimes recorded in marls and shales with few arenaceous intercalations (subtype Id).

The soils of the subtype Iia are located on the oldest alluvial terraces. The soils of the subtype Iib correspond to recent alluvial deposits (made of clays, often in lenses, with layers of silt and sand or gravel); they are the most widespread and are very heterogeneous.

The type III is constituted by the colluvium of loess and weathered loess that form thin sheets that cover the flats of the oldest terraces.

The swelling/shrinking soils of Oltrepo Pavese are characterized by a very high to high swelling potential (Fig. 2), with the exception of the soils of aeolian origin (Meisina and Najjar, 2004). The soils are saturated or quasi-saturated (saturation degree Sr>85%) for most of the year. Only in exceptionally dry periods the soils become unsaturated and the water content drops near or below the shrinkage limit. The maximum depth of the active zone (zone of seasonal moisture content variation) is ranging from about 0.8 to 2.8 m, with the lowest values corresponding to soils of subtype Ia.

A rainfall analysis was carried out in order to determine drought events responsible for shrinkage of clay soils. From the weather records for the period 1951–2003 the rainfall deficit of the area was obtained by calculating the arithmetic difference between the monthly water budget (difference between precipitation and potential evapotranspiration) and the average monthly water budget calculated over a 40-year period (1961–2002). The cumulated rainfall deficit was smoothed...
computing the moving average on a period of 5 months, which was considered suitable to detect long-term trends (Fig. 3). It identifies the duration \(N\) (number of months) and the intensity \(I\) (amplitude of the curve) of the drought. The comparison between lines A (difference between the average monthly rainfall deficit and

Fig. 2. (A) Swelling–shrinking soil susceptibility map of the Oltrepo Pavese. (B) Swelling–shrinking susceptibility map of the eastern sector of the Po River Plain showing the distribution of the Permanent Scatterers.
the monthly rainfall deficit standard deviation) and B (difference between the average monthly rainfall deficit and the double of the monthly rainfall deficit standard deviation) and the cumulated rainfall deficit evidences the drought severity (severe where the curve exceeds line A, very severe when it exceeds line B). The region has experienced many drought periods during the last two decades (Fig. 3). The last major droughts were March 1989–August 1993 (the most severe drought of the period) and May 1998–September 2000.

Water content profiles, measured in different months (April, August and December) of wet period (1994–1995) and of drought period (2000), were used, according to the method of BRE (1996) to provide a qualitative estimate of the magnitude of vertical movements that could occur seasonally and following exceptionally dry periods. Cyclic annual vertical movements of around 50–70 mm were calculated for soils Ia, Ib and IIb, 20–25 mm for soils IIa and III. After exceptionally dry periods vertical movements can reach up to 50–100 mm depending on the thickness of the active zone, the highest values being in alluvial soils (IIa, IIb). The results are a crude estimate of vertical movements that will probably occur (e.g. foundation pressures would reduce the magnitude of the heave).

3.3. Water pumping

One shallow phreatic aquifer and several deeper aquifers of both phreatic and confined type are distinguished in the Quaternary cover of the Po River Plain, consisting of an alternation of less permeable sediments (silt and clay) and more permeable horizons (gravels and sandy clays of the Po river sediments and the Apenninic rivers) (Fig. 4). The configuration of the aquifers is also affected by buried folded and faulted structures of the

Fig. 3. Rainfall deficit curve. The rainfall deficit was obtained by calculating 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 1961–2002); see text for additional explanations.

Fig. 4. Schematic cross section of the eastern sector of Oltrepo Pavese plain near Broni, after Peloso and Cotta Ramusino (1989) (see Fig. 1 for location). (1) Clay and silt; (2) sand and gravel; (3) tertiary substratum; (A, B and C) main aquifers.
Tertiary substratum. The neotectonic movements controlled the thickness of the superimposed Quaternary sedimentary cover, influencing the aquifer hydrogeology (Braga and Cerro, 1988). The thickness of the Quaternary sediments decreases from west to east, reaching the minimum close to the outcrop of the substratum near the Stradella thrust (Fig. 1).

Peloso and Cotta Ramusino (1989) compared the annual withdrawal and the average annual water table levels during the 1969–1986 periods of the named B aquifer (Fig. 4), in the eastern part of the Oltreo Pavese, where the groundwater is pumped at a depth of 15–30 m (Fig. 5). In 1971–1979 the piezometric level was below the average value for the period 1946–1986. This corresponds to an increase of the groundwater pumping (from 2 × 10⁶ to 3.6 × 10⁶ m³/year). After this period the withdrawals decreased until 1993 (from 3.5 to 1.7 × 10⁶ m³/year). Nevertheless, the water table lowered during a very intense drought (1989–1993) (Fig. 3). Between 1994 and 2000 the withdrawal slowly increased again, but the water table lowered only after 1997. There is a correlation between the amount of the groundwater pumped and the water level fluctuations, but the water table drawdown is also related to other factors such as intense drought periods. Unfortunately, no information about the amount of associated land subsidence is available.

4. Methods and data acquisition

A review of the basic principles of SAR interferometry and relevant processing techniques is beyond the scope of this work. For this and for comprehensive information on a Permanent Scatterers (PS) technique the reader is referred to Colesanti and Wasowski (2006–this issue) and to Ferretti et al. (2000, 2001).

In total 77 ERS scenes acquired between 1992 and 2001 by the ESA sensors along descending orbits and 26 images acquired in the same time-span along ascending orbits were used for the interferometric analysis. About 95,000 PS were identified in the descending data set, while only 3800 PS were extracted from ascending scenes. This was mainly due to the limited number of images acquired along ascending orbit and the unfavourable temporal and geometrical (satellite baseline) distribution of the acquisitions. PSs typically correspond to man-made structures (buildings, poles, antennas).

The geocoding accuracy of the PS locations is around +15 m in easting and +4 m in the north–south direction, while the estimated accuracy of the elevation values was usually better than 2 m.

Most of the PSs are in the plain area, where the density of man-made structures is high. Very few PS were detected in the mountain sector (the southern part) because of the unfavourable land-cover (vegetation and agricultural fields) and morphological (steep slopes) characteristics.

The Line of Sight (LOS) displacement rates vary from +5 to −16 mm/year and are relative to a reference point, located in the town of Casteggio (Fig. 1), and assumed motionless. Values have a precision usually better than 0.5 mm/year, depending on the amount of available data, the local PS density (a key element in the estimation of spurious atmospheric phase components), and the distance from the reference point.
For each PS it is also possible to recover the time series of the LOS displacements (with respect to the reference PS). The precision on single measurements is related to coherence and ranges from 3 to 5 mm for a coherence threshold of 0.65.

The PS coherence \( (c) \) was classified into three classes (1: \( c < 0.65 \); 2: \( 0.65 \leq c < 0.85 \); 3: \( c \geq 0.85 \)), considering the reliability of the displacement measurements. Generally, PS with coherence less than 0.65 were not taken into account. PSs with high coherence, and therefore high reliability \( (c \geq 0.85) \), represent the 10% of the total number of PSs.

The results of the Permanent Scatterers interferometric analysis were integrated in a GIS with the geological (lithology and structures), the hydrogeological (depth to the water table) and geotechnical characteristics of the soils, as well as with landslides and the damaged buildings databases.

Two types of PS analyses were performed: Standard Permanent Scatterers Analysis (SPSA) and Advanced Analysis (APSA). The SPSA is suitable for mapping the territory at a regional scale, in order to identify unstable areas, that deserve further detailed studies. PSs 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. A linear motion model is assumed and the information about the linear velocity is extracted.

The Advanced Analysis (APSA) is suitable for small areas where a full exploitation of the information content of the satellite data is required. This analysis requires skilled technical staff and it is time-consuming depending on the size of the area and on the number of images. APSA allows to search for non linear motions and for PS with variable characteristics in time, significantly increasing the PS density. Motion vs. time series were provided for all advanced PS in Oltrepo Pavese.

The SPSA analysis allowed to identify the clusters of PSs indicating ground movements (uplift and subsidence), to verify or update the state of activity of the unstable areas characterized by low displacement rates (<3 cm/year), to update the landslides inventory (with the identification of new phenomena) and to verify the relationship between PS velocity and damages on individual buildings.

Following the SPSA, 20 test sites were selected based on the site characteristics (e.g. swelling/shrinkage, landslide) and the degree of geological risk (Italian Law 267/98), the availability of prior information and the presence of PS showing displacement rates higher than +1 mm/year and less than −1 mm/year. For each test area, a geological model was built integrating the geological–geomorphological characteristics of the site with the geotechnical data obtained through penetrometer tests, boreholes and laboratory tests. The rainfall deficit was also studied. For the test sites located in the plain, the ground water table fluctuations and the influence of the ground water pumping were also taken into account and compared with the PS LOS displacement time series.

Four test sites, corresponding to areas with the highest displacement values (Voghera, Broni, Poggio Ferrato and Varzi, Fig. 1) were selected for the APSA analysis.

5. Permanent Scatterers study of the Oltrepo Pavese

5.1. General distribution of PS

The standard PS velocity distribution allows identifying two areas of subsidence and two of uplift in the Oltrepo Pavese.
The two subsiding areas were clearly identified in the towns of Voghera and Broni (with PS density equal to 510 and to 986 PS/km² respectively) (Fig. 1). In Voghera, the ground movement in the eastern part of the town was unknown. This subsidence of 10–30 mm from 1992 to 2000 (1–3 mm/year) could be related to the presence of over 6–7 m thick clay deposits in the subsoil. In the town of Broni clay shrinkage phenomena have already been known as the cause of considerable damage to buildings. The SPSA analysis detected a ground subsidence in the north-eastern part of Broni of about 10–22 mm from 1992 to 2000 (1–5 mm/year).

Two slowly uplifting areas (1–1.5 mm/year) were identified in the towns of Casteggio and Varzi, with PS density equal to 397 and to 136 PS/km², respectively.

5.2. PS and landslides

The analysis of the standard PS data sets and landslides in terms of distribution and state of activity shows

![Map of the Ruinello landslide showing the distribution of the Permanent Scatterers (PS) and their velocity; landslide activity is based on geomorphological criteria.](image)

**Fig. 7.** (A) Map of the Ruinello landslide showing the distribution of the Permanent Scatterers (PS) and their velocity; landslide activity is based on geomorphological criteria. (B) PS Line of Sight (LOS) displacement series (Standard Analysis—SPSA), \( \Delta V_{1992-2000} = 15-20 \) mm. (C) Location of the Ruinello test site.
that 7% of the descending PS are located on known active, dormant or inactive landslides (Fig. 6). This low percentage is related to the limited number of buildings on landslides bodies. Most PS fall on inactive landslides and only 25% of the PS are located on active or dormant landslides.

Nevertheless, about 25% of PS present on dormant and active landslides shows a velocity greater than +1 mm/year (maximum LOS displacement rate = 3.8 mm/year) and thus they indicate an uplift; this is consistent with the location of these PS on the accumulation zones of some deep landslides. An example is the Ruinello landslide (Fig. 7), which is situated in the north-eastern sector of the Oltrepo Pavese. The landslide develops between 265 and 155 m a.s.l. and it modified the Versa River course. This movement involves the bedrock (Val Luretta Formation), which consists in marls, calcareous marls with interbedded scaly clays. The bedrock is highly deformed and weathered and is locally covered by thick eluvial–colluvial
soils consisting of high plasticity clays with blocks of limestone and marl (up to 4–6 m thick in the hollows). The eluvial–colluvial soils are characterized by a very high swelling/shrinking potential. Boreholes and refraction seismic profiles identified three main layers: the first, with a velocity $V_{p1}=390–630$ m/s and a thickness of 4–6 m, corresponds to the recent landslide material; the second horizon, with $V_{p2}=775–1750$ m/s and 6–20 m thick is the material of an older inactive slide; the third one with $V_{p3}>2000$ m/s, corresponds to the bedrock. A shallow water table is present in the eluvial–colluvial soils and in the fractured bedrock. It intersects the ground surface in the hollows, favouring the concentration of water and the build up of pore pressure. Several shallow movements overlie the main landslide body. Intense rainfall, the weakness and structure of the bedrock and the cover, together with the presence of a shallow water table has been identified as the main predisposing factors. From the 1970s the inactive landslide has been affected by several reactivations, which caused many damages to the buildings in the areas of Ruinello and Cà dei Cristina.

During the last 20 years different sectors of the landslide have been stabilized through the construction of drainage systems (Fig. 7A) consisting in trench drains and sub-horizontal drainages, but some areas are still in movement, as highlighted by very severe damages in the buildings located in the accumulation zone.

Indeed, moving PS were detected on the landslide toe, where the village of Ruinello is located, with displacement rates ranging from +2 and +3.8 mm/year (15–20 mm in the period 1992–2000) (Fig. 7B). The moving PSs correspond to damaged buildings. Elsewhere non-moving PS were detected.

The PS analysis allows to re-assess the state of activity of several landslides and suggested a change from inactive to active category. In some cases, however, the presence of moving PS on inactive landslides did not seem to be associated to landslide activity and the cause of movement could be linked to the settlement of the foundation soil of the buildings which are PS. An example is represented by the inactive landslide of Zebeda, located in the central part of Oltrepo Pavese (Fig. 8). This instability corresponds to a translational

---

Fig. 9. Map of the Michelazza village showing the distribution of the Permanent Scatterers (PS) and their Line of Sight (LOS) velocity (Standard Analysis—SPSA); landslide activity is based on geomorphological criteria.
Fig. 10. (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 village 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 a-a’ and b-b’ shown in Fig. 11.

Fig. 11. Longitudinal sections of the Poggio Ferrato landslide (see Fig. 10 for locations). (1) M. Vallassa Sandstone; (2) Monte Lumello Marls; (3) M. Piano Marls; (4) Chaotic Complex; (5) weathered sandstone; (6) landslide; (7) fracture; (8) borehole.
slide which involves the Zebedassi Limestone (calcareous flysch), consisting of fractured calcareous marls with interbedded shales and clays. Geomorphological field surveys, carried out during 1994 and 2000, did not recognize any features indicative of movements and therefore the slide was classified as inactive. In the central portion of the slide, near the village of Zebeda, the PS indicated continuous displacements ranging from $-7$ to $-13$ mm/year (Fig. 8B). More detailed field checks, carried out in 2003 after the SPSA, found that the buildings on the landslide body are subjected to subsidence phenomena. This is demonstrated by the lowering of the buildings with respect to the sidewalks. The cause of movement (predominantly vertical) could be related to the geotechnical characteristics of the foundation soil.

A limited number of previously unknown unstable areas have also been detected through the use of the PS. They correspond to calcareous reliefs or to ridges located on the sides of the active or dormant landslides. Fig. 9 shows the case of the small village of Michelazza, built on limestones (Val Luretta Formation) dipping towards the slope. Around the relief some active and dormant complex landslides were detected; they develop in the clayey facies of the Val Luretta Formation. By photointerpretation the relief did not seem to be involved in landsliding. The standard PS analysis measured displacement rates ranging from $-3$ to $-5$ mm/year, in good agreement with the presence of several damaged buildings detected during field checks.

Subsiding movements ($-11$ mm/year) were detected on sandstone slabs (caprocks) lying on a deformable clayey substratum. This phenomenon occurs on the borders of the slabs where the rock is highly fractured, with sets of subvertical joints which separate sandstones blocks; weathering and softening can occur in the clayey soils. Advanced PS analysis was accomplished for the case of the active landslide of Poggio Ferrato, which is considered as one of the most hazardous zones in Oltrepo Pavese (Braga et al., 2003).

The active landslide of Poggio Ferrato is located on the northern border of a sandstone slab lying on a clay substratum. A geological description of the area is available in Braga et al. (2003). The landslide is classified as an active complex failure with a source area affected by a roto-translational slide developing downhill into an earth flow with a NNW–SSE direction (Fig. 10A). The landslide has a maximum width of about 250 m, a length of 1500 m and a total surface of about 90,000 m². The landslide involves the Chaotic Complex formation. The depletion zone is constantly active. In the last 50 years, the slide crown has...
retrogressed by 250 m. In the same period the flow advanced of about 855 m. A serious increase in the movements was recorded in December 1996, after a long period of heavy rainfall. The earth flow moved with displacement rates of 10 m/day and advanced about 160 m. This reactivation caused cracks to open in nine buildings in the northern part of the old village of Poggio Ferrato, built on the sandstone slab, near the active landslide scarp (Fig. 10B).

The new village of Poggio Ferrato is built on the crown of an other large landslide (Fig. 12), now inactive and with the same characteristics of the active, previous described, movement.

The site investigation in the Poggio Ferrato area consisted of 16 boreholes 9–40 m deep, trench pits and geophysical surveys (Fig. 10B). A geological model of the site was derived. Different thicknesses (from 7 to 30 m) of the sandstones (M. Vallassa Sandstone) have been observed in the boreholes (Fig. 11). This can be explained by the existence of an important SW dipping fracture, which indicates differential settlement and sinking of sandstone blocks along the border of the slab. Most of the damaged buildings are located near this discontinuity. The geomechanical and geomorphological surveys indicate the presence of a lateral spread and block type slope movement (Braga et al., 2003). The stability conditions of the slope are governed by the groundwater circulation in the sandstone, above the impermeable clayey and marly substratum. Springs runoff cause the softening of the clayey soils and this contributes to the evolution of slope movements. Monitoring activities consisted in piezometric level measurements from April 1998 to January 1999 and open crack measurement in the damaged houses (Fig. 12), from June 1997 and February 1999. The crack monitor placed on the northern wall of the building located on the above mentioned fracture showed horizontal displacements of 12–13 mm (towards NW) and vertical (downward) displacements of 5 mm during this period.

The results of the advanced PS analysis are shown in Fig. 12. A limited number of advanced linear PS (12) were identified in the old village of Poggio Ferrato close to the active landslide scarp. More PS (48) were detected in the eastern part, where the new village of Poggio Ferrato is located. The PS time series highlight a significant settlement of the sandstone slab at the old village (25–35 mm in the period 1992–2000); no significant movements were detected in the new village (PS velocity between $-1$ and $+1$ mm/year). The PS velocity ranges between $-1$ (southern part of the old village) and $-3$ mm/year (north-eastern part). The SAR data support the hypothesis of a differential settlement and sinking of sandstone blocks along the borders of the slab near Poggio Ferrato. The lack of PS in the north-western part

---

Fig. 13. Geological model of the Poggio Ferrato slope (see Fig. 12 for locations of the geological sections A and B).
Fig. 14. (A) Linear and nonlinear advanced Permanent Scatterers (PS) in the town of Broni (Advanced Analysis—APSA). (B, C, D, E) Time series with Line of Sight (LOS) velocities of representative PS.
of the old village, that is the nearest to the landslide crown and where the larger number of damaged buildings are concentrated, could be related to the magnitude of the ground displacements, probably exceeding the 14 mm/35 days threshold, making this interferometric analysis unfeasible.

The available PS displacements series show that the settlement is continuous during the period considered. An interpretation of the lateral spread phenomenon at Poggio Ferrato is represented in Fig. 13, which shows two different local slope conditions. These can be identified by characteristic morphological features and different advanced PS displacement rates:

Condition 1 (Fig. 13A): opening of vertical joints originated by tectonic stresses, differential settlement and sinking of the sandstone blocks occurs on the border of the slab and large complex slide develops (active Poggio Ferrato landslide); PS detect settlement and their velocity ranges between $-1$ and $-3$ mm/year.

Condition 2 (Fig. 13B): retrogression of the landslide causes detachment of blocks, which are translated donwslope; then the movement stops. This stage corresponds to the inactive landslide, where the new village of Poggio Ferrato is located; PS are stable (displacement rate between $-1$ and $+1$ mm/year).

5.3. PS and swelling–shrinking soils

Mapping swelling/shrinking soils generally requires a great number of laboratory geotechnical data, which are expensive, time-consuming and provide information only at a limited number of points. New methods to study and identify such soils from remote sensing have recently been the subject of research (Van der Meer, 1999). Spaceborne spectrometry has been found to give fairly good information on the geotechnical properties of the soils in relation to their mineralogy (Olsen et al., 2000). Chabrillat et al. (2002) found it possible to distinguish between the spectral response of three indicators of potentially swelling clay minerals based on airborne sensor data. Kariuki et al. (2004) reports the combined use of the spectral enhancement
techniques and the ETM+ panchromatic band visual interpretations of the gilgais to establish a swelling soil location map.

Vertical displacements detected through the PS technique represent another type of information useful to evaluate swelling/shrinking potential.

The information from the Standard Permanent Scatterers Analysis (SPSA) was integrated in a GIS environment within the swelling/shrinking soils map of the area (Meisina, 2002) (Fig. 2). In the Po plain the areas of subsidence at Broni and Voghera could be related to the presence of clay soils (subtype IIa) with high volume change potential (Fig. 2B). This is confirmed by the geotechnical data (swell strain in the active zone reaches up to 2.5%) and by the types of damages to the buildings (the cracks appeared at the end of 1980s with a worsening in 1998–2000, they are progressive and generally close up during the wet seasons and open up again during the dry seasons).

We discuss hereafter the results of the advanced analysis (APSA) regarding the town of Broni (Figs. 1 and 14). Several buildings (single storey family residences), founded on conventional concrete shallow strip footings, were damaged in the last years (Fig. 15).

The town is built on very heterogeneous alluvial fan deposits and a detailed geological model of the urban area was obtained from the integration of the geological–geomorphological characteristics of the site with the geotechnical data (65 penetrometer tests, 28 boreholes and laboratory tests, Fig. 15). Silty clay and clayey silty deposits of high to very high swelling/shrinking potential constitute the first layer. They are soft soils (tip resistance qc = 1–2 MPa) and their thickness varies from 4 m in the western part to 20 m in the northeastern part (Fig. 15). In the western sector of the town, thin lenses of silt and sand are interbedded. The underlying layers consist, from top to base, of sand and gravel, silty clay, gravel and Tertiary marls.

Two aquifers (Fig. 4) separated by a silty clay aquitard are present. The groundwater is pumped from the deepest (B), which is a semi-confined aquifer with a depth from 10 to 25 m. The water table fluctuation in drought periods reaches 2.5–3 m. The thickness of the active soil zone in the period 1992–2001 was 2.8 m. The moisture regime of the soil could also be influenced by a seasonal perched water table.

The ASPA identified linear and nonlinear PS. Ground displacements were detected in the northern and in the eastern part of Broni, near the Apennine fringe, where nonlinear PS are present (Fig. 14A). The time series of nonlinear PS displacements show a significant change after May 1998 (Fig. 14B–C), which corresponds to the beginning of the settlement phase that reached 14–22 mm at the end of autumn 2000. In order to quantify the subsidence during the period May 1998–November 2000, a map of the ground displacements was constructed by interpolating (Radial Basis Functions) the movements of individual PS (Fig. 15).

To interpret the possible causes of the subsidence we confronted the PS results with rainfall deficit and groundwater withdrawal data. The PS displacements are concordant with the rainfall deficit in the northern and eastern sector of the town, where the clay soils have the highest thickness (Fig. 14B–C). However, a great number of municipal water wells are also present in the zone with the maximum subsidence rate. Indeed, the comparison between the withdrawal and the PS displacements (Fig. 16) shows that the increase in water...
pumping and the settlement occur in the same period, i.e. after 1998. The relationship between PS displacement, rainfall deficit and withdrawal is not evident in the eastern part of the town (Fig. 14D), where thin lenses of silt and sand are interbedded within the clay soils and this reduce the swelling/shrinking potential of the clay. Therefore, the subsidence could be related to the shrinkage of the soil in the drought period and to the lowering of the water table associated with pumping wells.

6. Discussion and conclusions

The application of the PS technique in the Oltrepo Pavese area confirms its high capability for detecting and mapping ground deformation at sub-regional and local scales, in synergy with in-situ conventional surveys (e.g. geological, geomorphological, hydrogeological). The main disadvantages encountered in Oltrepo Pavese were (1) the lack of PS in the southern sector of the area, where large rotational and translational slides are concentrated and (2) the generally limited number of PS on landslide bodies. The interpretation of the interferometric results, in terms of temporal evolution of the ground deformation, is also limited by the scarcity of ground control data (e.g. inclinometer, topographic surveys) for the period 1992–2000.

The PS analysis at a sub-regional scale (SPSA) detected slow ground deformations ranging from +5 to −16 mm/year, and resulting from various processes (landslides, swelling/shrinkage of clay soils and water pumping). The analysis, carried at a 1:10,000 scale, is simple (comparison in a GIS between the PS distribution and the maps and data of different databases developed during previous studies), but requires a good knowledge of the geological, geotechnical and hydrogeological characteristics of the study area. Furthermore, the reliability of the very slow LOS deformation rates (1–5 mm/year for subsidence and 1–1.5 mm/year for the uplift) may need to be validated with other data (e.g. GPS surveys or optical levelling).

A useful application of the SPSA is in landslide inventory updating (detection of unstable areas, updating of the information about the state of activity). The Oltrepo Pavese landslide inventory was only partially updated through the use of standard PS analysis, due to the limited number of landslide bodies with PS (7% of the inventoried landslides). Nevertheless, some previously unknown unstable areas were detected through the use of the SPSA. They correspond to calcareous reliefs or to ridges, located on the sides of the known landslides, and require more detailed studies to understand the causes of movement.

The state of activity of the mapped landslides, originally determined following only geomorphological criteria, was re-examined by considering the PS distribution/velocity and the outcomes of the subsequent field surveys. This resulted in the modification of the state of activity of several landslides. In some cases, however, the presence of moving PS on inactive landslides did not seem to be associated to mass movement processes but rather to ground deformation phenomena linked to the geotechnical properties of the foundation soils.

The SPSA also allowed to obtain useful results in the identification of slowly evolving slope movements as lateral spreads of sandstone slabs (caprocks) lying on a deformable clay substratum. These lateral spreads were originally investigated through geomorphological and structural studies, which indicated that all the sandstone slabs in Oltrepo Pavese could be affected by this phenomenon. The standard PS analysis revealed the presence of settlements of sandstone blocks along the borders of some slabs, which is one of the most important evidences of lateral spread activity. Furthermore, the advanced PS analysis of the Poggio Ferrato landslide supported the geological interpretation of the associated lateral spread phenomena, and aided in the understanding the mechanism and the evolution of these movements.

In the case of the Ruinello landslide (with a deep inactive landslide overlain by younger shallow movements), PS deformation rates and time series revealed: (1) progressive uplift in the accumulation zone of the order of 1.3–3.8 mm/year (15–30 mm from 1992 to 2000), consistent with the presence of severely damaged buildings; (2) slight subsidence or no movement in the upper portion of the landslide.

The study of the temporal evolution of the landslides on the basis of PS displacement time series was difficult not only for the scarcity of ground control data, but also for the existence of other superimposed factors related to the subsoil processes (e.g. swelling/shrinkage of clay soils) and to the behaviour of man-made structures which correspond to PS radar targets. Further studies will be devoted to the comparison of the PS time series with the damaged building characteristics (soil geotechnical characteristics, typology of foundation and structure, period of appearance of damages, period of execution of remedial works), trying to discriminate the contribution of the different factors on PS displacement.

The study of ground deformation and swelling/shrinking hazards with PS technique was a difficult task. The phenomenon of swelling and shrinking of clay soils has a seasonal component, which is difficult to identify in the PS time series. Nevertheless, the analysis allowed
to identify clusters of PS marking two areas of uplift and two areas of subsidence, where local authorities may concentrate future detailed geological studies and risk mitigation actions.

In particular, in the Po plain, the comparison between the swelling/shrinking soil map and the PS velocity distribution helped to identify and to map two areas of ground subsidence. The advanced analysis coupled with the geological model of one of these areas (Broni) suggested the influence of the soil shrinking processes and water pumping on the vertical movement during the drought period 1998–2000: the relative importance of these two factors is difficult to distinguish. The subsidence based on the LOS ground movements recorded by the PS technique ranges from −1 to −5 mm/year. These figures are generally lower than the calculated rates of shrinkage for the same drought period.

Acknowledgements

The study was supported by Regione Lombardia (project “Attività di elaborazione ed interpretazione geologica ed idrogeologica dei dati radar PS per l’area dell’Oltrepo Pavese in Provincia di Pavia”). The landslide inventory was supported by the Province of Pavia and coordinated by Prof. G. Braga and L. Natale of University of Pavia. The authors also acknowledge the Municipality of Broni, Val di Nizza, Voghera, the A.C. A.O.P., the Comunità Montana Oltrepo Pavese, Prof. G. Macchi, Dr. D. Baroni, Eng. Barbero, Dr. G. Guado, for providing some of the geotechnical and hydrogeological data. The authors are grateful to Dr. G. Ioriatti, Ing. R. Malaspina and Geom. D. Bartilucci of Lombardia Region for the data on the damaged buildings, and to Dr. F. Conconi and F. Verri for the help in data processing and editing. Finally, the authors would like to thank two anonymous reviewers and Dr. A. Ferretti and Dr. J. Wasowski for their valuable comments.

References


