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Integration of persistent scatterer interferometry and ground data for landslide monitoring: the Pianello landslide (Bovino, Southern Italy)

Abstract We present an example of integration of persistent scatterer interferometry (PSI) and in situ measurements over a landslide in the Bovino hilltop town, in Southern Italy. First, a wide-area analysis of PSI data, derived from legacy ERS and ENVISAT SAR image time series, highlighted the presence of ongoing surface displacements over the known limits of the Pianello landslide, located at the outskirts of the Bovino municipality, in the periods 1995–1999 and 2003–2008, respectively. This prompted local authorities to install borehole inclinometers on suitable locations. Ground data collected by these sensors during the following years were then compared and integrated with more recent PSI data from a series of Sentinel-1 images, acquired from March 2014 to October 2016. The integration allows sketching a consistent qualitative model of the landslide spatial and subsurface structure, leading to a coherent interpretation of remotely sensed and ground measurements. The results were possible thanks to the synergistic operation of local authorities and remote sensing specialists, and could represent an example for best practices in environmental management and protection at the regional scale.

Keywords Persistent scatterer interferometry · Integrated landslide monitoring · Inclinometric borehole measurements

Introduction

The Daunian Apennines in Apulia (Southern Italy) are intensely affected by land instability, mainly related to very shallow soil slips and to relatively deeper (> 20 m) landslides (Ciaranfi et al. 2011; Cotecchia et al. 2015; Cotecchia et al. 2016, among others). These latter represent the most important geological risk factor for the area, as they frequently affect the outskirts of towns and infrastructures (national railways, highways, and other strategic communication routes). The abundance of landslides in the Daunian Apennines is strictly related to the prevailing fine-grained material (silts and clays) forming the flyschoid units cropping out in the area, and to the generally low relief energy of the slopes (10° – 15°) (Spalluto et al. 2015 and reference therein). Daunian landslides are usually described as having a complex kinematic behavior, where significant internal distortion of the material occurs. Nevertheless, the dominant movement takes place along shear surfaces bounding the moving mass (e.g., Ciaranfi et al. 2011). This kind of landslide typically starts as a roto-translational slide evolving, after the post-failure stage, into a flow having slow velocity ($\lesssim 1.6$ m/year; Cruden and Varnes 1996), occasionally reaching moderate velocities (~ 13 m/month) during main re-activations (e.g., Parise et al. 2012; Cotecchia et al. 2015). The rate of displacements follows seasonal trends, being lowest in summer and highest in late winter/early spring, when very high piezometric heads are recorded down to large depths (Cotecchia et al. 2014).

The ground monitoring of land instability in urbanized areas is a complex, costly, and time-consuming activity. It requires the realization of a network of monitoring stations (e.g., boreholes equipped with inclinometers and piezometers) aimed at measuring several critical parameters, and the work in the field of a highly qualified staff of technicians for collecting the data and for checking the correct functioning of the installed instrumentation. A crucial role for the monitoring of the landslide activity is played by slope inclinometers, installed in boreholes drilled in different sectors of the landslide body. They measure the subsurface horizontal displacement of the landslide mass along the shear surface and are used to determine the magnitude, rate, direction, depth, and type of landslide movement. This information, used in synergy with other surface and subsurface monitoring data, can give important clues for understanding the cause and behavior, and thus devise remediation of a landslide (Stark and Choi 2008).

Recently, remote sensing has come forward as an effective additional tool in the monitoring of landslide terrain displacements, thanks to the synoptic view (large area coverage) and relatively low costs of remotely sensed images (Wasowski and Bovenga 2014). While optical sensors remain the most used kind of data to identify landslide areas, synthetic aperture radar (SAR) sensors, and particularly multi-temporal techniques based on the identification of stable scatterers, known as multi-temporal (SAR) interferometry (MTI), has demonstrated to be a valuable aid in monitoring hazard areas undergoing displacements (Tofani et al. 2013b; Di Martire et al. 2016b).

The joint use of remote sensing MTI and in situ data depends on the characteristics of the displacement phenomenon, on the movement components measured by the in situ instruments, and on the projection of the ground movement along the space-borne SAR line of sight (LOS). Examples aimed at the monitoring of unstable slopes date back more than a decade (see, e.g., Farina et al. 2006; Singhroy 2009; Tofani et al. 2013a), and new experiments are constantly being reported (Del Soldato et al. 2018; Frattini et al. 2018). Examples of synergy between environmental authorities and remote sensing analysts to monitor terrain instabilities are increasing at national (Di Martire et al. 2017; Rosi et al. 2018) and European level (Wilde et al. 2018).

Mostly, ground data are compared with remotely sensed data, for validation purposes. This is the typical situation when both can be assumed to sense the same process, e.g., with a known displacement direction, as in the case of leveling measurements applied to subsidence (Ketelaar 2009) or uplift (Refice et al. 2016), or GPS applied to seismic deformations (Casu et al. 2006). For the specific application to landslides, comparison of ground and remote measurements is possible when processes consist, e.g., of earth or debris flows in the maximum slope direction, which occurs on shallow landslides (Calò et al. 2014; Bovenga et al. 2017). In such

cases, scalar measurements can be back-projected onto the assumed direction of motion, and both can be quantitatively compared. More generally, instead, no direct comparison is possible, but integration among independent ground- and satellite-derived measurements can be attempted; experiments in this sense have been presented for wide-area surveys (e.g., Casagli et al. 2016; Calvello et al. 2017) and more local analyses of deep-seated landslides (e.g., Bianchini et al. 2013; Di Martire et al. 2016a).

While comparisons between MTI and in situ data were more frequent in early validation studies, nowadays, as MTI techniques are considered as well assessed, a more interesting use of MTI is as a complementing integration to the in situ measurements.

In this work, we present an example of integrated analysis at a local scale. The present work should be regarded as an example of virtuous synergy/feedback between remote monitoring and in situ inspection. Original knowledge of unstable areas in the wide region of Daunia, Apulia (Southern Italy) led local authorities to team with remote sensing specialists to investigate ongoing displacements through MTI analysis of SAR data from the European ERS and ENVISAT satellites. Results of this collaboration highlighted active displacements affecting critical areas (inhabited, with valuable/historic infrastructures, etc.) over which it was important to focus ground investigations. In the case of the small hilltop town of Bovino, these consisted in the installment and continuous monitoring of boreholes equipped with inclinometers and other instrumentation. Such ground data, mostly sensitive to the horizontal components of terrain displacement, were finally coupled to more recent MTI results (more sensitive to subvertical displacement components) from data acquired by the new European Sentinel-1 constellation, to give a consistent, qualitative model of the full 3D displacements of a local landslide affecting a versant of the southern outskirts of the town.

In the following, after a description of the geological setting of the test site, we describe the used remote sensing and ground instrumentation data and methods. Then, we describe the results of the remote sensing and ground measurements, and, in the “Integrated analysis” section, we investigate in more detail the complementarity between inclinometer deep displacement data and the surface displacements of PS objects close to each of the boreholes. This allows to sketch a qualitative but consistent scheme of the landslide structure and process in the “Discussion” section. Finally, we derive some conclusions.

Geological setting

The northwestern part of the Apulia region (Southern Italy) belongs to the foreland thrust belt system of Southern Apennines (Mostardini and Merlini 1986; Casero et al. 1988; Patacca et al. 1990; Pescatore et al. 1999; Patacca and Scandone 2007). This system includes, from west to east, the following geological domains: Apennines chain, Bradanic trough, and Apulian foreland (Fig. 1).

The allochthonous units of the Apennines chain are thrust over the terrigenous autochthonous succession of the Bradanic trough foredeep basin, which rests in turn on the Meso-Cenozoic carbonate units of the Apulian foreland.

The town of Bovino lies on an asymmetric ridge along the margin of the Daunian Apennines, i.e., the Apulian sector of the Southern Apennines chain (Fig. 1), where Cretaceous to Miocene formations of the Daunian tectonic unit crop out

unconformably covered by Pliocene thrust-sheet-top deposits (Jacobacci and Martelli 1967; Ciaranfi et al. 2011; Spilotro et al. 2016). Lithostratigraphic formations of the Daunian tectonic unit are made up of flyschoid deposits showing a large intraformational lithological variability (Dazzaro and Rapisardi 1984, 1987, 1996; Dazzaro et al. 1988; Ciaranfi et al. 2011). In the study area, the outcropping succession of the Daunian tectonic unit corresponds to the *Flysch di Faeto* fm (Langhian-Serravallian in age). This formation can be informally divided in the following units: the lower clayey-marly and the upper calcareous-marly (Ciaranfi et al. 2011). The clayey-marly unit of the *Flysch di Faeto* fm is locally made up of repeated alternations of massive clayey silts and sandy-clayey silts with scattered gravels and thin-bedded calcarenites; the calcareous one is made up of thick beds of calcarenites showing thin clayey silt intercalations. This succession conformably overlays the clayey succession of the *Flysch Rosso* fm (Cretaceous-Langhian in age), and conglomerates of the Bovino Synthem (middle Pliocene in age) unconformably overlay it (Fig. 2). The *Flysch di Faeto* succession is locally deeply deformed by thrusts and normal faults and, at the outcrop scale, shows several minor tectonic (jointing, folds, and minor faults) and sedimentary structures (slumpings) that partly or totally disrupt the original bedding (Ciaranfi et al. 2011).

The highly heterogeneous lithology of the clayey member of the *Flysch di Faeto* and the deep tectonic deformation seem to be the main driving factors of the widespread landslide activity in the area. Actually, active and dormant landslides mapped in the area mostly formed in correspondence of silty deposits and, subordinately, in the calcareous ones (Fig. 2). According to the Italian Landslide Inventory Project (AAVV 2007), active and dormant landslides of the Daunian Apennines can be classified as flows, as roto-translational slides, and as landslides having a complex kinematic behavior. Many of these landslides, in the last decades, underwent reactivation processes (Parise et al. 2012; Spalluto et al. 2015) producing severe damage to structures and infrastructures in the Daunian Apennines.

The Pianello landslide is set up onto the fold-bent fault (i.e., ramp anticline) formed over the thrust surface crossing the southern border of the old town of Bovino (Fig. 2). This landslide affects only the clayey-silty deposits of the clayey member of the *Flysch di Faeto* fm and forms a roto-translational body, almost 740 m long and 250 m wide, with toe emerging along the left-side valley of the Biletra River (Cotecchia et al. 2016). The southern outskirts of the town of Bovino extends over the depletion area of the Pianello landslide, where several buildings show structural damage mostly linked to the recent activity of the landslide (Palmisano 2016; Palmisano et al. 2016; Cotecchia et al. 2016).

Data and methods

Legacy SAR data MTI analysis

To understand the extent of occurrence of recent displacements, and thus the activation state of several landslides in the Daunia Apennines, a regional-scale MTI monitoring activity was programmed and carried out in 2008, exploiting available SAR databases (Alemanno et al. 2009).

A dataset of 42 ERS-1/2 images, acquired in descending geometry, i.e., with the satellite trajectory headed at an azimuthal angle

Fig. 1 Geological setting of the foreland thrust belt system of the Southern Apennines (modified from Ciaranfi et al. 2011). Coordinates refer to the UTM WGS84 33N reference frame

of about 188° , covering the interval 1995–1999, and 24 ENVISAT images, acquired in ascending geometry, i.e., with the satellite trajectory oriented at a $\sim 352^\circ$ azimuthal angle, spanning the interval May 2003–June 2008, was processed through the Stable Point Interferometry over Un-urbanized Areas (SPINUA) PSI processing chain (Bovenga et al. 2005). Both satellites observed the Earth surface from about 800-km height to the sensor's right side along a LOS looking down at an incidence angle of about 23° from the vertical, with a nominal ground resolution of about $20 \times 5 \text{ m}^2$ (range $\times$ azimuth). The two SAR data time series were processed to

extract displacement information over persistent scatterers (PS), i.e., objects on the Earth surface with stable scattering characteristics (Ferretti et al. 2001).

Ground instrumentation

The regional analysis of legacy SAR time series highlighted several cases of ongoing displacements over parts of known landslide bodies in the Apulia region. This prompted the Apulia River Basin Authority to carry out a ground survey. In particular, a subsurface monitoring network was installed on the active

Fig. 2 Geological and geomorphological map of the study area (scale 1:10,000). Note that the Pianello area (sketched after an unpublished field survey) is mapped as an active landslide. Coordinates refer to the UTM WGS84 33N reference frame

body of the Pianello landslide and in surrounding areas. From each borehole, a detailed lithostratigraphic log was reconstructed and undisturbed samples for geotechnical laboratory tests were collected. The boreholes were equipped with either inclinometer casings or piezometric cells. Here, we focus on the results of the inclinometric survey in order to quantify the subsurface displacements of the landslide body, in an area where the detected surface PS displacements could be associated to several superficial evidences of ground deformation, as well

as damage on structures and infrastructures mostly recorded in the Pianello neighborhood of the Bovino town.

The readings of inclinometric data cover a period of 8 years, and were performed in two different, partly overlapping, monitoring surveys, using two different biaxial probes. The first survey, accomplished by technicians of the Foggia Province, started in December 2008 and ended in November 2015. The second one, accomplished by technicians of the Apulia River Basin Authority, started in July 2015 and ended in September 2016, with an average reading frequency of about one per month. The instrumentation

used on each borehole in the first campaign (Foggia Province) consisted of a SISGEO probe and an Archimede Datalogger read-out unit, while for the second campaign (Apulia River Basin Authority), it consisted of an RST Digital Inclinometer System and an HP iPAQ hx2410 Pocket PC readout unit. Both probes contain two perpendicular accelerometers, so only two passes of the probe are required to measure movements in the two different directions: one accelerometer measures the tilt in the plane of the inclinometer wheels, tracking the longitudinal groove of the casing, while the other one measures the tilt in the plane perpendicular to the wheels. In both surveys, the measurements were taken starting at the bottom of the inclinometer. Subsequent readings were made as the probes were raised incrementally, in 1-m (Foggia Province) and in 0.5-m intervals (Apulia River Basin Authority), respectively, up to the top of the casing. Since different probes were used, two different zero readings were obtained at the beginning of the two surveys. The difference between the zero and the subsequent readings was used to determine the change in the shape and position of the initially vertical casing. Comparison of the verticality of the casing with time and the width of the slide provides an insight to the magnitude, rate, direction, depth, and type of landslide movement (Stark and Choi 2008).

Sentinel-1 MTI analysis

Following the ground survey, more recent SAR data, acquired by the Sentinel-1 sensor, were processed, with the aim of integrating the in situ information. The Sentinel-1 constellation is currently composed of two twin satellites (Sentinel-1/A and Sentinel-1/B, respectively), the first one active from April 2014 and the second from April 2016, and observes the Earth from about 693-km altitude, at a nominal ground resolution of about $5 \times 20 \text{ m}^2$ (range $\times$ azimuth), thus comparable to that of the legacy sensors. Forty-one Sentinel-1/A images, acquired in ascending geometry at an incident angle of 34° , were processed, through the same SPINUA PSI processing chain used for the legacy ERS and ENVISAT data, spanning the period from October 2014 to March 2016.

Results

SAR MTI results

Over the town of Bovino, the legacy SAR data analysis showed the presence of several PS exhibiting displacements in the LOS direction, located on the Pianello landslide area. As shown in Fig. 3a, displacements from ERS data, acquired in descending geometry, thus with LOS projection on the ground looking approximately westwards, are positive (towards the sensor), while those in ENVISAT data (Fig. 3b), acquired in ascending geometry, with LOS projection on the ground roughly looking eastwards, are negative (away from the sensor). Assuming a generally steady displacement process in the two observation periods, this indicates the presence of a horizontal component of motion, besides the vertical one. The local slope in the landslide area is of a few degrees, with the surface normal pointing on average towards SSE. Consequently, MTI is able to catch just a small portion of this movement component, due to the satellite LOS projection on the ground, which in both geometries is directed roughly along the E–W direction.

The Sentinel-1 sensor–detected PS points exhibit instead a more dense distribution, over the whole town areas as well as some of the outskirts, than the legacy data shown in Fig. 3, as can be seen in Fig. 4. This is due to the generally smaller spatial baselines, thanks to the greater orbital precision, and the increased acquisition frequency (once every 12 days for the case of Sentinel-1/A, compared to 35 days for both ERS and ENVISAT). The great majority of the Sentinel-1 PS points exhibiting significant displacement rates fall within the limits of the Pianello landslide.

On the landslide area, the strongest PS motions are recorded close to the detachment area at N, and at the southern limit of the urban area, roughly in the middle of the landslide area. Several PS are located close to the locations of the installed inclinometers.

Borehole inclinometer data results

Figure 4 shows the location of the continuous boreholes drilled for the inclinometric survey. Inclinometers are marked by colored triangles, green in case of no relevant displacement, orange in case of relevant shear displacement, and red in case of rupture of the casing. The boundary between “no relevant” and “significant” displacements was set considering the total inclinometer accuracy, which is a combination of both random and systematic errors of the system. We set for the used probes an empirically assessed accuracy of about 7 mm per 30 m of casing, similarly to what proposed in the recent literature for analogous probes (e.g., Stark and Choi 2008). Displacements measured by the inclinometers located outside the landslide body in the Pianello locality were always below the system accuracy, and thus, they were classified as no relevant (green triangles in Fig. 4). Displacements measured by the inclinometers located inside the main landslide body were always far above the system accuracy, and thus classified as significant because they recorded active shear deformation (orange and red triangles in Fig. 4). More in detail, data plotted on incremental displacement and cumulative displacement graphs outline clear shear bands at different depths, which evolved in the rupture of the casings for boreholes S6, S9, and S12 (red triangles in Fig. 4). In the following section, an integrated analysis is proposed for displacements recorded by each of the borehole inclinometers, and the closest Sentinel-1 PS.

Integrated analysis

A first qualitative assessment can be made by looking at Fig. 4, which shows Sentinel-1 PS points represented by dots with color proportional to the LOS displacements according to the colorbar in the figure and inclinometers indicated by colored triangles. A good spatial correlation exists between the displacements measured by the inclinometers and those measured by remote sensing. Outside the limits of the Pianello landslide, both measurement sets do not record significant displacements, while within the landslide limits, both record movements, except for the inclinometer installed in the borehole S10, which did not record any displacement, probably because the borehole depth did not reach the stable ground below the shear surface, as detailed later on.

We remark, as also reported by other authors (Cotecchia et al. 2016) that the Pianello landslide has a complex structure which cannot be described as a simple translational landslide, and includes non-negligible vertical displacement components. Hence, since no clear assumption can be made about the actual direction of the displacements in the various parts of the landslide,

Fig. 3 **a** ERS, descending geometry, and **b** ENVISAT, ascending geometry average LOS velocity PS maps. Colored points indicate PS, with color proportional to velocity according to the respective colorbars. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Background is an optical image from Google Earth. The outline of the Pianello landslide (purple area) and the crown limit (in yellow) is also shown

displacements from inclinometers and PS cannot be directly compared. To show this, consider the scheme reported in Fig. 5. Panel a shows the generic 3D view of the vectors relevant to the measurement of the displacement of a generic point P on the ground, for which we have both inclinometric measurements (as a vector $\vec{v}_i$ in the horizontal plane, projected onto the LOS vertical plane according to Eq. 2 below) and satellite-derived PS displacements (as a vector $\vec{v}_{PS}$ in the LOS plane). Panel b shows the azimuth LOS

and displacement angles, respectively, within a horizontal plane. Panels c and d represent a section of the sliding surface in the vertical plane containing the satellite LOS vector, with different cases. In panel c, we consider the case of point P moving along the slope direction (as typical of shallow landslides). In this case, as the actual displacement direction is assumed to be known, the horizontal component of displacement can be back-projected on the slope vector and then onto the LOS, through the formula

Fig. 4 Sentinel-1 average LOS velocity PS map. Colored points indicate PS, with color proportional to velocity according to the colorbar. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Background is an optical image from Google Earth. The outline of the Pianello landslide and the crown limit is shown. The map also shows the locations of the inclinometer boreholes installed by AdB (labeled S1 to S12), as well as the two borehole inclinometers (labeled 12 and 14, respectively) reported in Cotechchia et al. (2016) (colored triangles). Blue lines indicate terrain section profiles (see Fig. 16)

$$v_{h,LOS} = v_h \cdot \frac{\sin(\theta + \xi)}{\cos \xi}, \quad (1)$$

where θ is the satellite incidence angle and ξ is the local “reduced” slope angle. Here, v_h is the component of the inclinometric displacement v_i , horizontally projected onto the vertical plane containing the LOS, i.e.

$$v_h = v_i \cdot \cos(\alpha - \phi), \quad (2)$$

where α and ϕ are the inclinometer and the LOS azimuth angles, respectively (Fig. 5b). The reduced slope angle can be obtained from the true slope angle, ω , as

$$\xi = \text{atan}[\cos(\alpha - \phi) \cdot \tan \omega] \quad (3)$$

(see also, e.g., Plank et al. 2012). In this case, $v_{h,LOS}$ can be directly compared to the displacement recorded by nearby PS, represented in the figure as v_{PS} . In panel d, we show the case in which the ground displacement of point P has a non-negligible vertical component besides the horizontal one, so that the actual

displacement vector is not parallel to the slope. In this case, the two quantities $v_{h,LOS}$ and v_{PS} are not directly comparable, as the former clearly underestimates the actual LOS projection. This is generally the situation in our case.

Anyway, as can be seen from the general direction of the slope on the landslide area, in most cases, the horizontal component of motion (recorded by the inclinometers) is almost perpendicular to the LOS projection on the ground, so that the horizontal projection factor in Eq. 2 is considerably small.

Moreover, inclinometric measurements generally apply to points below the surface, as usually measurements close to the borehole surface end are affected by errors due to instrument handling procedures. Thus, in case of complex (not shallow) landslides, this would further complicate a hypothetical direct comparison between ground and satellite-based displacement measurements, which, instead, provide useful complementary information.

This is the case of the present work, where the horizontal components of the displacements, coming from the inclinometers, and the subvertical ones coming from the PS, are well suited for an integrated analysis.

In the following subsections, we analyze the signals from the most relevant inclinometers individually, integrating, wherever possible, the information about subsurface displacements with that about displacements of nearby PS on the surface, in the sense explained above.

Fig. 5 Simplified scheme for the comparison/integration of inclinometric vs. PS measurements. Panel **a** shows a schematic 3D view of the satellite trajectory and LOS direction for a generic point P on the ground moving along a vector $\vec{v}$, for which both inclinometric, $\vec{v}_i$, and satellite PS, $\vec{v}_{PS}$, measurements are assumed to be available. Panel **b** illustrates the view in the horizontal plane, where α and ϕ are the displacement vector and the LOS azimuth angles, respectively. Here, $\vec{v}_h$ is the component of the inclinometric displacement in the LOS plane. Panels **c** and **d** represent schematic views of a generic terrain profile in the vertical plane containing the satellite LOS, where θ is the satellite incidence angle and ξ is the local “reduced” terrain slope angle. **c** In case of displacements known to be parallel to the slope direction, the horizontal inclinometric displacements can be back-projected onto the LOS direction, according to Eqs. 1, 2, and 3, and then directly compared to the LOS displacements measured by nearby PS. **d** In case of displacements not parallel to the surface slope, the previous comparison cannot be made, as the projected $\vec{v}_{h,LOS}$ would underestimate the real LOS component of the displacement, measured by nearby PS

Borehole S6

Borehole S6 (Fig. 6a) was drilled to the depth of 20 m. The logged stratigraphy shows, from the bottom to the top, the following lithologies, covered by about 1.5 m of ground: (i) from 20 to 18 m, green clayey silt with scattered gravels; (ii) from 18 to about 13 m, yellow sandy-clayey silt with scattered gravels; (iii) from about 13 to 8 m, black sandy-clayey silt; and (iv) from 8 to 1.5 m, brownish sandy-clayey silt (Fig. 7). The two closest PS points (circled red dots in Fig. 6a) have average LOS velocities of -29.5 and -27 mm/year, respectively. Their LOS displacement time series, plotted in Fig. 6b, show rather steady displacements.

Precipitations are also shown, indicated by the blue continuous line on the same plot, right vertical axis.

The original total depth of the inclinometer casing of the borehole S6 was about 20 m, as confirmed by the zero reading performed at the beginning of the first survey on 09 December 2008. However, the first reading, performed after a long time from the base one, on 28 September 2010, was not able to reach the bottom of the casing, and stopped at the measured depth of about 16 m. The zero reading of the second survey, performed on 28 July 2015, confirmed the results of the first survey, since the reading of the probe stopped at the depth of about 16.5 m.

Fig. 6 **a** Detail map of the area around the S6 borehole. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Colored dots represent PS; velocities are color-coded as in Fig. 4. **b** Displacement time series related to the two closest PS, highlighted by the dashed circles on the map in **a**, shown together with the daily precipitations (blue continuous line, right scale)

Moreover, the reading carried out on 26 August 2015, and a borehole video camera investigation, outlined a clear rupture of the inclinometer casing due to a shear surface located at this depth. The rupture of the casing occurred in the lithology identified as yellow sandy-clayey silt with scattered gravels (Fig. 7).

Borehole S7

Borehole S7 (see map in Fig. 8a) was drilled to the depth of 29 m. In the lower part of the borehole, from the base to the depth of about 12 m, gray clayey silt are alternated to thin-bedded calcarenite layers; from about 12 m to the surface, yellow clayey-sandy silt is alternated to black clayey-sandy silt (Fig. 9).

The original total depth of the inclinometer casing of borehole S7 was about 28 m, as confirmed by the zero reading performed at the beginning of the first survey on 09 December 2008. The first inclinometric survey recorded 10 readings, after the base one, from 28 September 2010 to 12 November 2015. In this time range, a shear band was detected at a depth between 4 and 8 m, as shown in the

resultant incremental displacement (Fig. 9a). The peak of the incremental displacement spike, i.e., the position of the inferred failure plane, is located at the depth of 7 m. The maximum resultant incremental displacement at this depth was about 48 mm, as seen in the reading performed on 12 November 2015 (Fig. 9a).

The greatest horizontal resultant cumulative displacement was measured at the depth of 5 m, where it reached about 105 mm (Fig. 9b). The lateral cumulative displacement showed that the first 2 m was neglected because it was related to the drift of the casing head in the uppermost part of the borehole.

The shear band is located within the lithology identified as yellow clayey-sandy silt (Fig. 9a, b). The direction of the displacement is 158° , about SSE.

Despite the fact that the second monitoring survey was carried out with a different probe and with a smaller sampling interval, the results of the two campaigns are similar. As a matter of fact, a shear zone was detected at similar depths, and the largest spike of

Fig. 7 Resultant incremental displacement graph recorded for borehole S6. Note that the casing broke at the depth of about 16.5 m, in yellow sandy-clayey silt. No time series are shown since the casing was already broken between the zero and the first reading

incremental displacement was located at the depth of 6.5 m (Fig. 9c). The maximum resultant incremental displacement at this depth was recorded on 16 September 2016 and corresponds to about 13.2 mm (Fig. 9c).

The cumulative displacement graph shows that the top of the shear zone was located at the boundary between two lithologies: the upper black clayey-sandy silt and the lower yellow clayey-sandy silt. However, the strength loss phenomenon occurred only on the lower lithology. The resultant cumulative displacement obtained from the combination of the two cumulative displacements measured on the two axes at the depth of 5 m is about 43 mm (Fig. 9d).

The time series plots of the displacements recorded by the inclinometers at about 7-m depth (Fig. 8c, d) outline the evolution of the strength loss phenomenon recorded in the shear band over time. The two time series (indicated by black squares and red diamonds, respectively) are derived from independent measurement sets, with different zero readings, and have been connected, just for sake of representation, by assuming similar displacement values at near dates. Periods of acceleration, deceleration, or constant rate displacement are detectable on the first survey time series, but a seasonal evolution cannot be clearly discerned because the number of readings is not sufficient (black squares).

In the time plot for the second survey (red diamonds), the rate of movement at the depth of 6.5 m shows accelerations in the following two time intervals: 24 September 2015–27 October 2015 and 23 February 2016–24 March 2016 (Fig. 8c). During the other detected periods, the rate of movement was almost constant. PS

time series for the targets within the moving mass, closest to the borehole, denote steady downward displacements with average LOS velocities of -25 , -25 , and -13 mm/year, respectively (Fig. 8b). In correspondence with the highlighted periods (evidenced by the two gray-shaded rectangles in Fig. 8b, c), some of the PS time series seem to show some sign of slightly abrupt variations in the displacement rates, although no clearer evidence is available. Peaks of precipitations (blue lines in all the plots, right vertical axis) seem to be also particularly strong in correspondence of the evidenced displacement discontinuities. Slight nonlinearities in PS displacement time series seem to appear in several other plots reported in subsequent figures. This would suggest some interesting time correlations with triggering factors, which however would require more in-depth investigations about the hydrology of the area, and is thus left for future work.

Borehole S9

Borehole S9 (see map in Fig. 10a) was drilled to the depth of 41 m. The logged stratigraphy shows, from the bottom to the top, two distinct stratigraphic intervals, covered by 6 m of ground: from about 41 to 17 m, green clayey-sandy silt are alternated to thin-bedded layers of calcarenite; from about 17 to 6 m, black clayey silt is alternated to yellow clayey silt and to a thin-bedded layer of calcarenite (Fig. 11).

The original total depth of the inclinometer casing of borehole S9 was about 40 m, as confirmed by the zero reading performed at the beginning of the first survey on 9 December 2008. The following readings show a clear shear zone at a depth interval between 16 m and 19 m (Fig. 11a). Moreover, the

Fig. 8 a Detail map of the area around the S7 borehole. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Colored dots represent PS; velocities are color-coded as in Fig. 4. The orange arrow indicates the approximate direction of the inclinometer displacement. b Displacement time series related to the closest PS within the moving mass, highlighted by the dashed circles in a, together with the daily precipitations (right scale). c Expanded plot of the highlighted area of the entire displacement time series (d) recorded on the S7 inclinometer at about 7-m depth. Gray rectangles in b and c highlight somewhat abrupt discontinuities recorded in the inclinometer and the nearby PS displacement trends, both temporally connected with precipitation peaks. Vertical offsets of all displacement plots are arbitrary. Vertical left scale in c and d is reversed for better comparison with PS downward displacement trends

resultant incremental displacement shows a spike at the depth of about 17 m. The maximum resultant incremental displacement at this depth was about 61 mm, as seen in the reading of 18 March 2015 (Fig. 11a). The resultant cumulative displacement at

this depth was about 92 mm (Fig. 11b). After this reading, the casing broke off at a depth of about 17 m, confirming, as expected, that the detected spike in the incremental displacement graph evolved in a failure plane.

Fig. 9 Results of the two inclinometric campaigns for borehole S7. **a** The resultant incremental displacement graph of the first inclinometric campaign shows a pronounced spike of about 48 mm at the depth of 7 m. **b** The resultant of the cumulative displacement graph shows a maximum horizontal displacement of about 105 mm at the depth of 5 m. **c** The resultant incremental displacement graph for the second campaign shows a pronounced spike at the depth of 6.5 m. At this depth, the maximum resultant horizontal displacement is about 13.2 mm. **d** The resultant cumulative displacement graph obtained at the depth of 5 m is about 43 mm

Fig. 10 **a** Detail map of the area around the S9 borehole. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Colored dots represent PS; velocities are color-coded as in Fig. 4. The red arrow indicates the approximate direction of the inclinometer displacement. **b** Displacement time series related to the closest PS, highlighted by the dashed circle shown in **a**, together with the daily precipitations (right scale). **c** Displacement time series recorded on the S9 inclinometer at 17-m depth

The time plot of the inclinometric displacements recorded at the depth of about 17 m (Fig. 10c) shows a roughly constant rate of about 17 mm/year starting from the first reading on 23 September 2010, with the exception of the time interval between the two readings carried out on 11 April 2013 and 09 October 2013, when the sliding was more limited (Fig. 11b).

The direction of movement measured during the last reading before the interruption of the casing was of 175° , i.e., approximately in SSE direction.

The zero reading of the second survey performed on 27 July 2015 confirmed the results of the last reading of the first survey, as the probe was not able to reach the bottom of the casing since it stopped at a depth of about 17 m (Fig. 11c). Moreover, the first reading carried out on 27 August 2015, and a borehole camera investigation, outlined a clear rupture of the inclinometer casing due to a shear surface located at this depth. The interruption occurred close to the boundary between the upper black clayey silt and the lower green clayey-sandy silt lithologies (Fig. 11c).

Fig. 11 Results of the two inclinometric campaigns for borehole S9. **a** The resultant incremental displacement graph shows a pronounced spike at the depth of 17 m. The maximum resultant incremental displacement at this depth is about 61 mm. **b** The maximum resultant cumulative displacement was about 92 mm at the depth of 17 m. **c** The incremental displacement graph of the second inclinometric campaign shows that the casing broke off at the depth of about 17 m close to the boundary between two lithologies: the upper black clayey silt and the lower green clayey-sandy silt

The closest PS (located more than 30 m from the borehole) records an average LOS displacement rate of about -16 mm/year, with lower rates in the first half of the time series (roughly until October 2015), and then a slightly steeper rate from October 2015 to the end of the series (see plot in Fig. 10b).

Borehole S10

Borehole S10 was drilled to the depth of 35 m (see map in Fig. 12a). The logged stratigraphy shows, from the base of the borehole to the depth of about 12 m, black and brownish clayey silts alternated to yellow and green sandy silts; from about 12 m to the surface,

Fig. 12 **a** Detail map of the area around the S10 borehole. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Colored dots represent PS; velocities are color-coded as in Fig. 4. **b** Displacement time series related to the closest PS, highlighted by the dashed circle, together with daily precipitations (right scale)

brownish clayey silt is alternated to thin-bedded calcarenite layers and covered by about 2 m of ground (Fig. 12). Only negligible movements were detected by the inclinometer (less than 4 mm), with no detectable shear bands (Fig. 13). Adjacent PS do register LOS displacements; the two closest ones show average LOS displacement rates of -18.5 and -14.5 mm/year, respectively, with a few episodes of nonlinearity (plot in Fig. 12b).

The shallow deployment depth of the inclinometer supports the hypothesis that the bottom of the borehole stays actually above the shear surface, so that no horizontal movements are recorded. Further support to this hypothesis comes from the measurements of an inclinometer in a deeper borehole, installed a few tens of meter upslope the one here described, and monitored within a different ground campaign, which recorded shearing at a depth of 46.5–48 m in a period from 2008 to 2014 (Cotecchia et al. 2016). The absence of other displacement discontinuities in the profiles reported in Cotecchia et al. (2016) for this inclinometer excludes the possible presence of a second, shallower shear surface.

Borehole S12

Borehole S12 was drilled to the depth of 40 m (see map in Fig. 14a). The local stratigraphy shows, from the bottom to the top, two distinct stratigraphic intervals, covered by about 1.5 m thick of ground: from about 40 to 19.5 m, gray clayey-sandy silts are alternated to thin-bedded layers of calcarenite and to a thin-bedded layer of green clayey silt with scattered gravels, and from about 19.5 to 1.5 m, yellow clayey-sandy silts are alternated to yellowish and brownish sandy silts (Fig. 15).

The original total depth of the inclinometer casing of borehole S12 was about 40 m. The zero reading was performed at the beginning of the first survey on 18 December 2008. The following readings show an evident shear zone at a depth interval between 24 m and 27 m (Fig. 15a). Moreover, the resultant incremental displacement graph shows a spike at a depth of about 25 m. The maximum resultant incremental and cumulative displacement at this depth was about 40 mm and 68 mm, respectively (Fig. 15a, b). After the last reading, the casing broke off at the depth of about

Fig. 13 Results of the two inclinometric campaigns for borehole S10. **a** The resultant incremental displacement graph shows only nonrelevant displacements (note the spike of about 4 mm at the depth of 11 m) since they fall within the settled inclinometer accuracy. **b** The lack of relevance in recorded displacements is also supported by the maximum resultant cumulative displacement of about 6 mm at the depth of 12 m. **c** The incremental displacement graph of the second inclinometric campaign shows that the inclinometer recorded only negligible displacements during the monitored time interval. **d** The maximum resultant cumulative displacement is also negligible because it is less than 2 mm

25 m, confirming that the detected spike in the incremental displacement graph evolved in a failure plane.

The time plot of the inclinometric displacements shows that the shear strength loss at the depth of about 25 m occurred at a mostly

Fig. 14 **a** Detail map of the area around the S12 borehole. Ground projections of satellite trajectories and LOS directions are indicated (white dashed and continuous arrows, respectively). Colored dots represent PS; velocities are color-coded as in Fig. 4. Red arrow indicates the approximate direction of the inclinometer displacement. **b** Displacement time series related to the closest PS, highlighted by the dashed circles in the map, together with the daily precipitations. **c** Displacement time series recorded on the S12 inclinometer at 25-m depth. Vertical left scale in **c** is reversed for better comparison with PS downward displacement trends

constant rate, with only a period of relative acceleration between the readings performed on 19 April 2011 and 02 August 2012 (Fig. 14c).

The direction of the displacements was oriented at about 125°, to SE.

The zero reading of the second survey, performed on 27 July 2015, confirmed that the inclinometer casing broke off at a depth of about 25 m. Moreover, the reading carried out on 28 October 2015, and a borehole camera investigation, outlined a clear rupture of the inclinometer casing due to a shear surface located at this depth. The interruption occurred in the gray clayey-sandy silt lithology (Fig. 15c).

The closest PS is located at a distance of almost 100 m from the borehole, and shows an average LOS displacement rate of –

18 mm/year, again with a few nonlinear spikes (Fig. 14b). We note that it is difficult to associate the two locations to a homogeneous block of terrain. Nevertheless, the overall picture is coherent with the presence of a subvertical displacement component at the location of the PS measurements and the presence of a horizontal component at the location of the inclinometric measurement, which is slightly downslope.

Discussion

The preceding description of inclinometric and PS displacements allows to get a coherent picture of the landslide phenomenon under study. The joint use of Interferometric Synthetic Aperture Radar

Fig. 15 Results of the two inclinometric campaigns for borehole S12. **a** The resultant incremental displacement graph obtained during the first campaign shows a pronounced spike at the depth of 25 m corresponding to about 40 mm. **b** At the same depth, the cumulative displacement graph shows a maximum resultant cumulative displacement of about 68 mm. **c** The incremental displacement graph recorded for borehole S12 does not show a time series because the casing was already broken before the first reading. Note that the casing broke off at a depth of about 25 m, in the gray clayey-sandy silt lithology

(InSAR) and inclinometers allows coupling the advantages provided by the two measurement methods, thus improving the monitoring capability and the knowledge about the spatial and temporal evolution of the displacements within the landslide body.

MTI approaches extend the area of the unstable slopes where displacement measurements are available, with respect to the few locations where inclinometers are deployed. In particular, Sentinel-1 data provide

PS maps with improved spatial density with respect to those derived from the legacy ERS/ENVISAT datasets (Fig. 4). MTI analysis improves the monitoring capabilities also in time. By using archived historical datasets, it is possible to go back in time to assess the stability of the area of interest, as performed in this study by using ERS and ENVISAT data (Fig. 4). Moreover, by linking results coming from different datasets, nowadays it is possible to provide monitoring periods of more than two

Fig. 16 Surface and subsurface integrated interpretation of the Pianello landslide (2× vertical axis exaggeration). **a** The longitudinal section AB crosses the central part of the landslide mass where the shear surface reaches the depth of about 50 m. **b** The longitudinal section CD crosses the eastern border of the landslide mass, where the shear surface is located at a shallower depth compared to the previous section. **c** The transversal section EF shows how the shear surface shows a concave up morphology, coherent with the nature of the Pianello landslide. The depth of the Flysch Rosso fm is interpreted (Cotecchia et al. 2016). Boreholes S4, S6, S7, S9, and S12 are from this study. Boreholes 12 and 14 are from Cotecchia et al. (2016). For map location of the three sections, see Fig. 4. The PS closest to the profiles is reported as colored dots on the surface, with color encoding velocity along the LOS direction. The LOS, projected onto the vertical plane containing the profiles, is drawn for each profile

decades (Bovenga et al. 2018). On the contrary, the maintenance of in situ measurement networks for such a long time is demanding, and homogeneous records acquired over long time intervals are difficult to find. Another important parameter for the analysis in time is the frequency of measurements. In the case of inclinometers, it depends on the in situ measurement campaigns, while for the InSAR data, it is determined by the satellite mission repeat time, which as mentioned, goes from 35 days of the legacy ERS and ENVISAT missions to 12 days for Sentinel-1/A, reaching 6 days for the Sentinel-1/A-B constellation, after April 2016. The time series reported in Figs. 6, 8, 10, 12, and 14 show clearly the improved time sampling provided by the InSAR analysis with respect to in situ inclinometric data. This is crucial, in particular, for detecting possible nonlinear displacements.

While InSAR techniques improve the monitoring capability on the ground surface both in time and space, the inclinometer measurements extend the displacement monitoring downward in the subsoil. This is important for modeling the sliding phenomenon by measuring the displacement depth and by relating the displacement to the subsoil lithology.

Finally, since InSAR and inclinometers measure different components of the actual displacement, they provide complementary information that can be used for both qualitative and quantitative assessment of the spatial and temporal evolution of the landslide movement.

The preceding general considerations, applied to the test case at hand, allow to propose a coherent picture for the overall structure of

the Pianello landslide. In fact, combining qualitatively the surface displacements measured in the horizontal direction by the inclinometers with those in the subvertical LOS direction by the SAR PSI data, a typical shape of a deep-seated landslide can be hypothesized. According to our results, the shear surface depth varies from about 6.5 m in correspondence to borehole S7, to about 17 m (S9), dipping finally to more than 25 m (S12). Moreover, the inclinometric monitoring campaign performed by Cotecchia et al. (2016) in the same area over a different network of inclinometers (see boreholes 12 and 14 in Fig. 16) outlined the occurrence of a shear surface located at the maximum depth of 46.5–48 m corresponding approximately to the central part of the landslide (Fig. 16a).

This interpretation is coherent with the nature of the landslide. The Pianello landslide shows the typical morphological features of a translational slide having a quite large depletion area upslope and a slide body resting upon a concave up shear surface (see also Cotecchia et al. 2016). Following this morphological evidence, it is expected, as shown in Fig. 16, that the depth of the shear zone is shallower along the border of the slide mass and maximum in its central part. As a matter of fact, the two inclinometers deployed in the S6 and S7 boreholes located close to the upslope boundary of the slide mass showed shallower shear zones than the ones deployed in boreholes S9 and S12, since these latter are located farther from the landslide boundary than the previous two (Fig. 16b). Following this reasoning, it is expected that the deepest position of the shear zone should be recorded by the inclinometer deployed in the borehole S10, but, unfortunately, this one was not drilled to the correct depth. Published data confirms this interpretation, since the shear zone in the central part of the Pianello landslide is located deeper at about 46.5–48 m (Cotecchia et al. 2016). As a result, the S10 borehole, drilled to the depth of about 35 m, was too shallow, and the inclinometric casing translated in conjunction with the main body of the landslide, preventing the reading of any movement (Fig. 16a, c).

PSI data also concur to give credit to this model: as described in the “Data and methods” section, surface displacements recorded along ascending and descending LOS directions by legacy sensors (Fig. 3a, b) show opposite signs of motion for the PS on the center of the landslide body, thus indicating the presence of a consistent horizontal component of motion, typical of roto-translational landslides, although it is worth to note again that the Pianello landslide has also a non-negligible vertical component (Cotecchia et al. 2016).

The more recent Sentinel-1 ascending data are consistent with this interpretation, and their increased spatial density allows to draw a rather coherent picture of the overall shape and limits of the moving part of the landslide, allowing to update to some extent these pieces of information: in particular, areas close to the SW limit of the landslide area (see Fig. 4) appear to be presently stable, while strong motions (up and beyond –20 mm/year) are detected in the highest portion of the moving area, at NW, suggesting a somewhat rapid evolution of the rupture surface in this area. This can also be seen in Fig. 16, where the PS closest to the three profiles has been drawn on the terrain surface, with the same colorbar proportional to LOS displacement velocity as in the previous figures.

Otherwise, most of the surface displacements recorded by the PS are consistent with the subsurface shear displacements

recorded by the inclinometers, both spatially and temporally, for the overlapping parts of the monitored time intervals.

Finally, comparison of the close moving PS data with the measurements of the single borehole inclinometer S10 helped interpreting its rather puzzling absence of any recorded movements, in spite of its position in the middle of the translational zone, by recognizing the abovementioned likely translational displacement of the whole borehole structure, caused by the insufficient borehole depth.

Conclusions

Our experiment is aimed at illustrating the integrated use of multi-temporal InSAR techniques and in situ inclinometers in slope instability monitoring, which allows overcoming some limitations of each of these measurement methods when used separately.

A first investigation, through analysis of legacy ERS and ENVISAT-derived PS data performed over large areas, highlighted the local presence of moving PS points, indicating active deformation within the limits of the known Pianello landslide, in the outskirts of the town of Bovino, in northern Apulia region (Southern Italy). These first results prompted local authorities to allocate resources and efforts, and guided the deployment of ground instrumentation, consisting in several boreholes equipped with inclinometers and other instruments, on locations chosen on the basis of the remotely sensed information, besides terrain knowledge.

Ground data collected during the following decade by the installed instruments were finally compared to new remotely sensed data, acquired by the Sentinel-1 satellites after the deployment of the ground instrumentation. Such new data basically confirm the presence of active displacements over the Pianello landslide, and can be merged with the information coming from the ground sensors to get a consistent picture of the shape and distribution of the spatial borders as well as the underground shear surface of the Pianello landslide.

This successful example of integration between remotely sensed and ground measurements, made possible thanks to the virtuous collaboration between remote sensing specialists and regional institutions, in this case the Basin Authority of the Apulia Region, serve, in our opinion, as an example of best practice in local environmental management and protection and one of the first, to our knowledge, to be adopted in a difficult environment such as a small hilltop town in Southern Italy.

The derived operational protocol is being planned to be repeated in the future over other test sites within the AdB jurisdiction, and could be an example of a standard to be followed at national scale.

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