Conventional and Innovative Techniques for the Monitoring of Displacements in Landslide Affected Area

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Abstract

This work shows a methodological approach for the joint use of geological and geomorphological studies and conventional/innovative monitoring data in densely urbanized areas at landslide risk. The methodology is applied to a test area in the Calabria region (southern Italy) extensively affected by several active landslides involving urban areas. These landslides have been studied and monitored via ground-based techniques for many years. In the study area the comparison and interpretation of DInSAR data with geomorphological studies and inclinometric monitoring has been carried out. The results obtained, thanks to the validation of remote sensed data via ground-truths, provide a further step towards the integrated use of DInSAR data within landslide risk mitigation strategies.

Keywords

Landslides • Multipass DInSAR • Natural hazards • Inclinometer monitoring

Introduction

Landslides are widespread all over the world with increasingly high societal and economic impact. Owing to the high risk for human life and/or structures and infrastructures associated with these phenomena, in the scientific literature several studies address landslide risk mitigation with the help of innovative monitoring systems.

In recent years, the multidisciplinary approach in the study of landslides has directed the scientific community towards the integrated use of conventional techniques and innovative satellite data. Among these, great attention deserves space-borne differential SAR interferometry which, although successfully tested with reference to different natural hazards, still needs detailed studies to fully exploit its applicability to landslide analyses.

In this work a test area representative of the typical geo-environmental contexts of Calabria and extensively affected by several active landslides involving urban areas has been selected. These landslides have been analysed via both geomorphological studies and field surveys and monitored via conventional geotechnical techniques for many years. Images acquired by Envisat satellite in the period from August 2003 to January 2010 have been firstly processed at both low- and full-resolution over the whole area and, then, interpreted on the basis of all the acquired knowledge.

The results obtained contribute to the development of procedures aiming at the detection and definition of kinematic features, which are typical of unstable areas within geologically homogeneous contexts.

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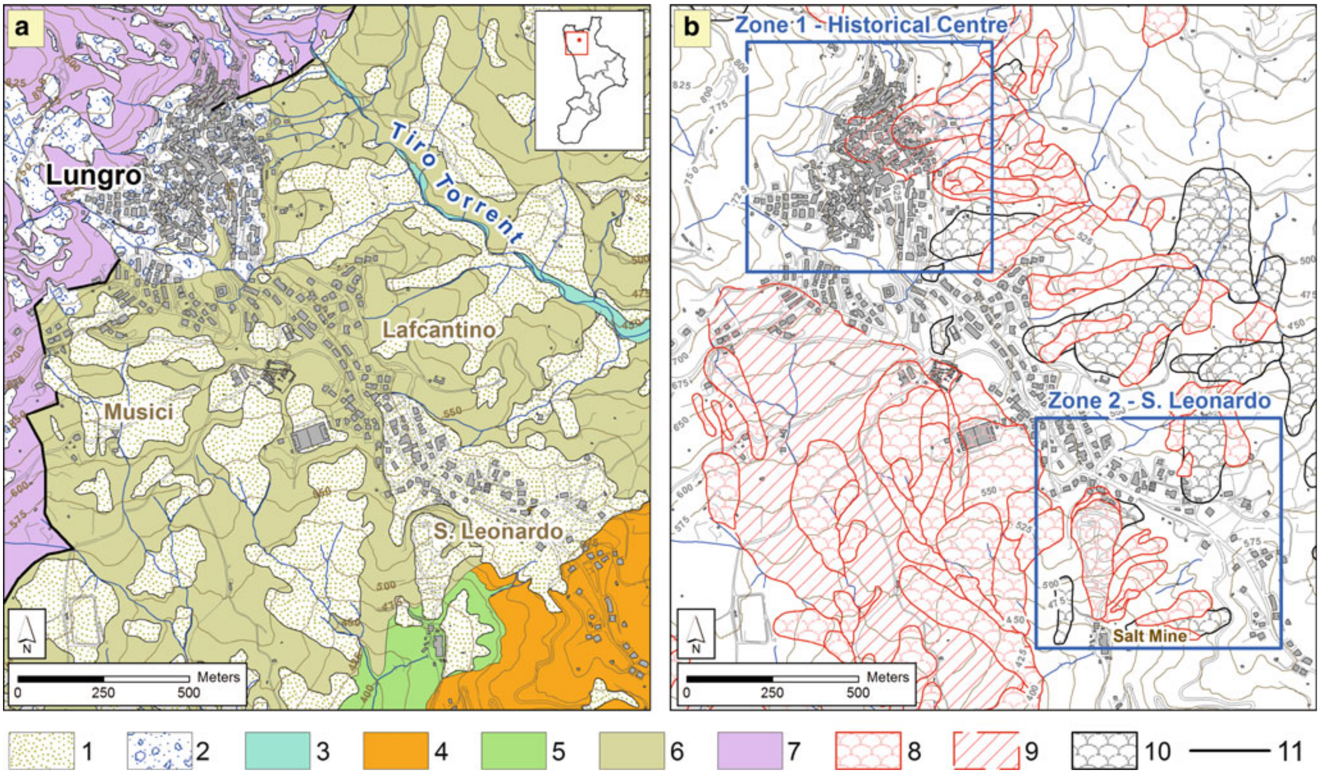

Fig. 1 (**a**) Geological map of the study area: (*1*) detritical-colluvial cover (Holocene); (*2*) detritical carbonate deposits (Holocene); (*3*) alluvial deposits (Holocene); (*4*) middle Pliocene-Pleistocene succession; (*5*) Middle Tortonian-Messinian succession; (*6*) Diamante-Terranova Unit (Lower Jurassic-Cretaceous); (*7*) Lungro-Verbicaro Unit (Anisian-Lower Burdigalian); (**b**) The landslide map of Lungro urban area: (*8*) active slide-flow; (*9*) uncertain boundary of active landslide zone; (*10*) dormant slide-flow; (*11*) tectonic contact

The Test Area

Geological and Geomorphological Sketches

The Lungro municipality (Fig. 1a, b), located in the north-west area of the Calabria region, is characterised by an extreme geological and structural complexity having direct impact on the instability of the town (both the historical centre and a newly developed urban area).

In this area Meso-Cenozoic sedimentary sequences of the Appennine domains are in tectonic contact with the Units of the Calabrian Arc (Amodio-Morelli et al. 1976) (Fig. 1a). In particular, in the north-western portion of the area, the Lungro-Verbicaro unit—whose base is made up of a thick sequence of green phyllites with carbonate intercalations potentially dating back to the medium Trias—crops out (Bousquet 1971; Bousquet et al. 1978; Ietto et al. 1992; Iannace et al. 2005). The basal portion of the sequence, gradually evolves into an interval of layers and banks of meta-limestones (Anisic-Carnic) which in turn evolves into clear dolomite rocks (Carnic). The Anisic-Carnic sequence is followed by an interval of saccharoid dolomite rocks (Norian–Rhaetian) with undistinguished layers, generally of cataclastic origin. Dark-grey and blackish calcareous rocks of Jurassic origin overlap the cataclastic dolostones in angular discordance and they are generally well stratified. The Lungro-Verbicaro Unit, lying next to the dwelled area of Lungro, moves towards the Ophiolitic Unit of Diamante-Terranova (Lower Jurassic-Cretaceous), with clear extensional tectonic contact (Fig. 1a). In particular, the cover of the Diamante-Terranova Unit crops out in the study area. The Diamante-Terranova Unit, being represented by phyllites and slate of prevalently dark grey colour is characterised by a good fissility. The foliation is commonly crinkled or wavy in appearance. Overall these lithotypes form a sort of "melange structure" made up of blocks and fragments of different nature (phyllites, clays and shales, calpionellids limestones and ophiolites) in a prevalently clayey matrix, derived from the degradation and claying of phyllites. An upper Tortonian-Messinian sequence lays, in angular discordance, on the metasediments of the Diamante-Terranova Unit (Di Nocera et al. 1974) and the sequence is made up of small outcrops of brown coarse sandstones, followed by grey-yellowish clays with gipsy sandstones, gypsum and some halite layers intercalations (Fig. 1a).

The early Miocenic succession then ends with sediments dating back to the middle Pliocenic-Pleistocenic period, represented by sandy-conglomeratic successions.

Some detritical deposits formed by stony elements of calcareous and/or dolomite origin dipped in a brown sandy and/or muddy matrix are present on the calcareous-dolomite slopes and at their base. A part of the inhabited area of Lungro, in the south western area of the village, has been built on such deposits. Moreover, some debris-colluvial covers and effective landslide debris, not clearly visible in the outcrops and with maximum thickness of about 10 m, are present prevalently on the phyllite unit of Diamante-Terranova.

The slopes in the area are affected by a large number of mainly active landslides (Fig. 1b) of different typologies, as testified in the scientific literature (Merenda 1990; Guerricchio et al. 1993, 2005; Gullà et al. 2006) and by aerial photo-interpretation carried out in different periods (1954, 1980, 1991, 2001).

The carbonate hillslopes above the historical centre are affected by topples and falls (Varnes 1978) due to many discontinuities and almost sub-vertical walls. In the same area (Fig. 1b), an arched scarp can be easily detected. This could be the outcome of an ancient rock block slide (Varnes 1978) as confirmed by the outcrop of carbonatic blocks (with volumes exceeding m^3 and thickness of over 10 m) within the area where the south-western sector of the historical centre develops.

Finally, the slopes with phyllites outcrops, characterized by a severe decrease of their physical and mechanical properties, are mainly affected by slope movements which can be classified as slides-flows (complex, according to Varnes 1978) and landslide zones. Landslide zone is not a real mass-movement type; it represents area affected by landslide phenomena of which it is impossible to distinguish the different bodies.

Landslides Activity

The instability of the area is well documented since long time (Almagià 1910). The analysis of historical data collected over the study area has highlighted that the historical centre of Lungro and the newly built up areas have been recurrently affected by landslide phenomena, usually slow ones, with a severe impact on both social development and business activities. Moreover, rainfalls seem to be the main cause of such slope instability in the area.

A building damage survey carried out in Lungro has highlighted that a number of the structures and infrastructures of the historical centre (see Zone 1 in Fig. 1b) displays many cracks which can be ascribed to slow ground displacements. In this regard, both geo-morphological analyses and field surveys suggest that the portion of the dwelled area affected by slow-moving phenomena corresponds to that mapped as "uncertain boundary of active landslide zone" in the Zone 1 of Fig. 1b; in this area diffuse and pervasive fractures were recorded to several buildings.

Moreover, as it can be noticed in Fig. 1b another portion of Zone 1 in the historical centre is affected by a slide evolving into flow towards Tiro torrent.

As for the stability of the structures/infrastructures, in the urban area, a key role seems to be played by their location along an extensional contact between tectonic units.

Around the second half of the last century an important urban development (Zone 2—San Leonardo in Fig. 1b) has taken place in the area southwards the historical centre. Despite the awareness of slope instability since past times, several houses, public buildings, facilities (such as council houses, health centres, a football ground, a new section of the graveyard, schools) as well as road network have been built up in the area. Recurring partial remobilisations and, therefore, the landslide activity are witnessed by some severe cracks and deformations in structures and infrastructures located inside the landslide bodies or in the vicinity of the main scarps. In particular, a 10-year observation activity shows that the buildings located in S. Leonardo Zone (two of which have lost their serviceability since 1998) have undergone a significant increase of the damage severity especially during the 2008–2011 period. This is testified by an increase in their tilt angles as well as by new cracks on previously undamaged buildings. Another problem of this area is caused by subsidence phenomena which may occur due to the presence of a salt mine disused since the 1980s and located at the slope foot.

DInSAR Data Analysis for the Test Area

Multipass DInSAR Algorithm and Image Dataset

Multipass DInSAR algorithms are widely used to retrieve information on displacement/velocity of the topographic surface. At present two classes of techniques are available for the analysis of phase signals in interferometric stacks: persistent scatterers interferometry (PSI) (Ferretti et al. 2000, 2001, etc.) and small baseline approaches (Berardino et al. 2002; Fornaro et al. 2009a, etc.). In the first class, the analysis is carried out at full resolution on stable scatterers in order to separate the atmospheric, topographic and deformation components. In the case of small baseline techniques, the scattering is supposed to be distributed within the resolution cell and spatial multilooking is implemented to enhance the phase stability. As a consequence of this operation, the spatial resolution is degraded with respect to the PSI approach. Nevertheless, a product of the small scale analysis is the estimate of the atmospheric phase delay (APD), which allows the implementation of a subsequent large scale analysis carried out at full-resolution (Fornaro et al. 2009b).

The radar analysis carried out in this work is based on a two-step approach. In particular, the low-resolution analysis (with pixel spacing of almost 80 × 80 m) was performed via the original Small Baseline Subset (SBAS) algorithm (Berardino et al. 2002), then the full resolution analysis (with pixel spacing of 20 × 5 m) was carried out according to the tomographic analysis proposed by Fornaro et al. (2009b). This latter is a super-resolution analysis which was applied here in order to detect the dominant scatterer, as usually done for PSI.

The image dataset consists of a total of 64 ENVISAT images acquired on both ascending (no. 35, track 86 frame 783 from 27th August 2003 to 27th January 2010) and descending (no. 29 track 222 frame 2,817 from 4th May 2003 to 21st February 2010) orbit.

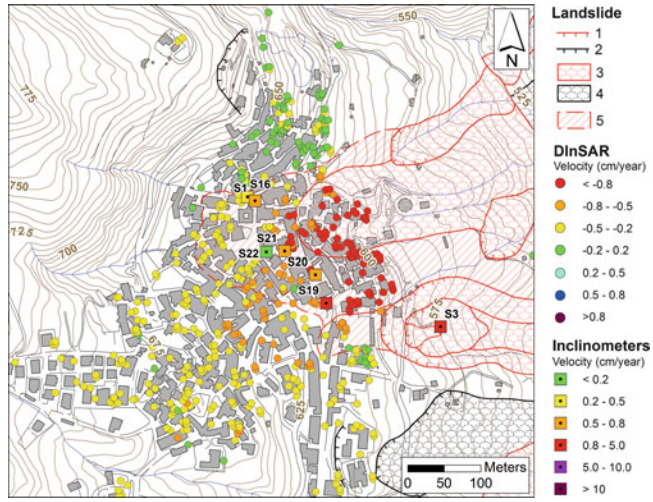

Fig. 2 The historical centre: distribution of full-resolution DInSAR data and benchmarks equipped with inclinometers: (*1*) active main scarp; (*2*) dormant main scarp; (*3*) active slide-flow; (*4*) dormant slide-flow; (*5*) uncertain body of active landslide zone

DInSAR Data Analysis

A preliminary product of DInSAR data processing is the low-resolution coherent pixel map. As described in Cascini et al. (2010) the analysis of low-resolution DInSAR data can be valuably used in analyses over large areas in order to get an overview of the features and kinematics in the area. Since the analysis in this work is carried out at large scale, low-resolution DInSAR data were only used to preliminarily test the remote sensing data coverage within the area of interest and to check evidence of general trends in velocity values as well. Then, the setting of the movement threshold of 0.2 cm/year (Cascini et al. 2009) allowed to preliminary highlight that all the covered landslides, independently from the state of activity reported on the landslide inventory map, contain at least one moving low-resolution DInSAR coherent pixel.

In order to further investigate this point the post-processed full-resolution (Fornaro et al. 2009b) DInSAR data were used (Figs. 2 and 3) over Zone 1 and Zone 2 of Lungro urban area as indicated in Fig. 1b. These data, indeed, can better suit analyses at large/detailed scale (i.e. 1:5,000; 1:2,000) aiming at the proper definition of both the boundaries and the state of activity of already mapped phenomena (Cascini et al. 2010). Moreover, DInSAR data can also be helpful in the detection of unmapped phenomena when geological/geomorphological information are available (Cascini et al. 2009).

Referring to the whole study area, DInSAR data highlight evidence of movements in different zones of Lungro town.

As for the historical centre (Fig. 2), full-resolution DInSAR data exhibit a good coverage also highlighting that different zones with varying ranges of DInSAR derived

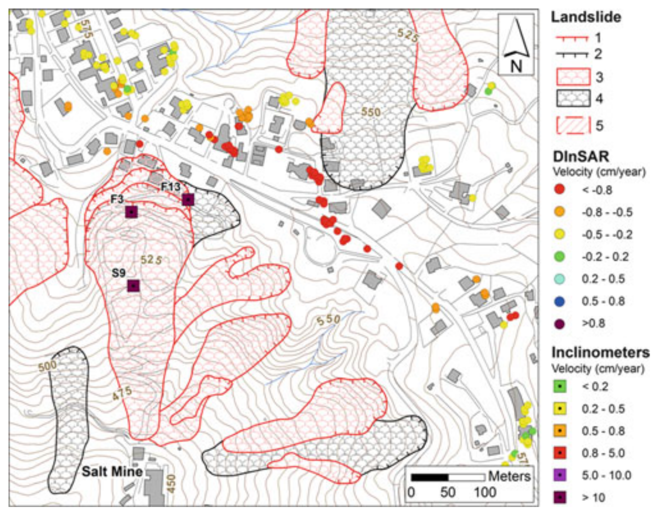

Fig. 3 The S. Leonardo area: distribution of full-resolution DInSAR data and benchmarks equipped with inclinometers: (*1*) active main scarp; (*2*) dormant main scarp; (*3*) active slide-flow; (*4*) dormant slide-flow; (*5*) uncertain body of active landslide zone

velocities (from 0 down to −1.33 mm/year) can be distinguished. Moreover, the map shows (Fig. 2) that the DInSAR coherent pixels with velocity values exceeding −0.8 cm/year (red dots) exhibit a spatial distribution which seems in agreement with the landslide inventory map. These data, indeed, overlay an active complex landslide involving Lungro old centre also involving portions of two other active complex landslides whose borders are not well defined on the basis of conventional methodologies. On the other hand, the DInSAR derived velocity values seem to decrease moving towards north and south-southwest directions.

With reference to S. Leonardo area (Fig. 3), the road heading to the centre stretches along the crest of the slope on whose right/left flanks groups of active/dormant complex phenomena are mapped. The analysis of DInSAR data reveals the presence of coherent pixels exhibiting velocity rates as high as 0.8 cm/year in proximity of both a group of complex landslides (whose widest portion is reported as dormant), on the north flank of the slope, and the head of an active complex phenomenon (on the south flank of the slope).

These data could be interpreted as due to a retrograding mechanism of the mapped landslides up to the road.

On the south-easternmost corner of Fig. 3—on the right side of the road—a group of moving full-resolution DInSAR coherent pixels, attaining velocity values as high as 1 cm/year, is located over a group of buildings. This area corresponds to that described in the previous section as located in proximity of the abandoned salt mine which could trigger subsidence-like displacements.

Validation and Integration of Kinematic Features

The study area has been analysed for long time via field surveys and geological/geomorphological studies in order to derive the geotechnical model of the most significant and representative landslide phenomena (Gullà et al. 2006). During the geotechnical investigations vertical inclinometers have been installed and measured; these data complemented other vertical lines derived from previous surveys started since 2006.

Monitoring results, which have provided useful indications on the kinematic features of the landslides affecting Lungro urban area, were then used for a preliminary validation and integration of DInSAR measurements.

To this end, first of all the displacement velocities derived from the vertical inclinometers located within the sectors under investigation have been computed referring to measures acquired at a depth of 1 m from ground level and across the whole reference period (February 2006 to May 2011).

The obtained velocity values range from 0.18 cm/year up to more than 50 cm/year. In Figs. 2 and 3 the selected vertical inclinometers have been labelled according to the DInSAR velocity classes in order to carry out a comparison with satellite data.

With reference to Fig. 2 inclinometric data seem to match the outcomes of geological and geomorphological analyses which outlined with difficulty the active state of the mass movements detected in the historical centre of Lungro. In particular, these phenomena are generally very slow according to Cruden and Varnes' (1996) classification since they exhibit velocity values not exceeding 5 cm/year. Moreover, Fig. 2 shows that the monitoring of deep seated

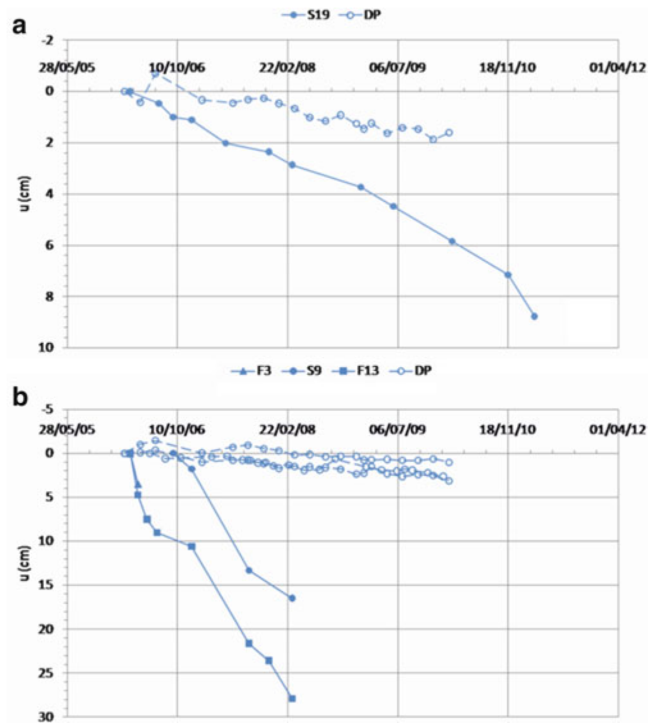

Fig. 4 Trend of displacements measured from inclinometer (S19, F3, S9, F13) and DP (full-resolution DInSAR coherent pixel) along the satellite Line Of Sight (L.O.S.): (**a**) historical centre, (**b**) S. Leonardo

displacement for the historical centre are consistent with the DInSAR—derived measurements.

As for the area of San Leonardo (Fig. 3), it can be noted that full-resolution DInSAR coherent pixel are scarcely present and the remote sensed velocity values do not match ground-based information. In this regard, it is worth stressing that velocity values relative to inclinometers on the southern slope of the ridge are always greater than 10 cm/year (with maximum values of over 50 cm/year), thus related to displacements too high to be detected via DInSAR data.

A preliminary quantitative comparison between the displacements measured by both each inclinometer and the nearest DInSAR coherent pixel is shown in Fig. 4a, b with reference to, respectively, the old town centre and S. Leonardo area. The discrepancy exhibited in the trends calls for further investigations concerning both considerations on the satellite acquisition geometry and the moving direction detected by each inclinometer.

Discussion

Geological and geomorphological studies carried out in the area under investigation provide a substantial reference framework of the complex condition of the instability affecting the structures and infrastructures of the urban area of Lungro.

In particular, such studies have outlined the most critical zones of the area: the historical centre and the newly developed urban area. In the first zone, the severe structural damages suffered from most of the buildings can be related to slow landslide phenomena that cannot be properly mapped from a geomorphological point of view; in the second zone, the deep cracks and deformations recorded to structures and infrastructures are the result of the several remobilizations of the landslides with a retrogressive evolution.

The analysis of full-resolution DInSAR data proved to be able to detect portions of the historical centre exhibiting different velocity values, thus helping in the definition of the state of activity of the related landslide phenomena. This could turn out to be extremely useful in further analyses aimed at forecasting related effects on the involved buildings.

With reference to S. Leonardo area, remote sensing data have provided information on the current boundary and kinematics of the covered phenomena also suggesting their likely evolution mechanisms (i.e. retrogression).

The outcomes of the displacement monitoring, carried out for a significant period of time, seem to confirm the kinematic characteristics of the sectors where velocities values fall within the intervals suitable for satellite analysis and—at the same time—they supplement such results in the sectors where velocities are faster.

Concluding Remarks

In the present work the potential of DInSAR data analyses carried out at both low- and full- resolution is highlighted with reference to the instability phenomena affecting the urban area of Lungro where previous detailed geological and geomorphological studies are available. In the area accurate displacement data obtained via inclinometer monitoring have also allowed the investigation of the kinematic features of the mapped very slow landslide phenomena.

The results obtained by means of this integrated approach show the great potential and complementarity of conventional and innovative techniques in analyses carried out at large scale and with reference to single phenomena occurring in complex geo-environmental contexts.

The comparison of the preliminary results obtained will be used for addressing further investigations in order to achieve an as much comprehensive view as possible of the kinematical features of the phenomena affecting the urban area of Lungro.

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