DIFFERENTIAL SAR INTERFEROMETRY TECHNIQUE FOR CONTROL OF LINEAR INFRASTRUCTURES AFFECTED BY GROUND INSTABILITY PHENOMENA

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ABSTRACT:

The Italian territory is strongly affected by ground instability phenomena and the occurrence of geological events, such as landslides and subsidence, is one of the main causes of damage to linear infrastructures, such as roads, bridges, railways and retaining walls, resulting in important socio-economic and human losses. To this aim, the frequent and accurate monitoring of surface displacements plays a key role in risk prevention and mitigation activities. In the last decade, a considerable interest towards innovative approaches has grown among the scientific community and land management institutions. In particular, Differential Interferometry Synthetic Aperture Radar (DInSAR) technique represents a useful tool to provide information on temporal and spatial evolution both of ground instability phenomena and of their interaction with man-made facilities, thanks to its accuracy, high spatial resolution, non-invasiveness and long-term temporal coverage, at reasonable costs. In this work, a GIS-semiautomatic approach, using Synthetic Aperture Radar data acquired by COSMO-SkyMed sensor, has been successfully applied to detect landslide-induced effects in terms of deformations of a linear infrastructure interested by slow-moving landslides in Campania Region (Italy).

1. INTRODUCTION

Man-made infrastructures may be affected by severe ground instability problems. In particular, the occurrence of landslides and subsidence phenomena is one of the main causes of related damage and accidents to roads and railways.

Deflections and distortions caused by ground instability can compromise safety of these transportation infrastructures. To this aim, monitoring the structural condition of infrastructure networks is essential to ensure their long-term resilience.

The implementation of a suitable method to periodically control infrastructure networks at different scales of analysis is also a key challenge: it may constitute an effective tool for remotely monitoring environmental risks and for planning mitigation measures.

Several in situ techniques are available for the local monitoring of infrastructure assets, including manual visual inspection, levelling, total station surveying, and GPS technologies (Lan et al., 2012).

These approaches provide highly accurate measurements of deformation at a single point, but can be highly expensive if a high density of measurements suitable for wide-scale infrastructure monitoring is required.

Necessity of an effective and very fast approach for monitoring of particular geological phenomena interacting with man-made structures, finds in the application of modern remote sensing techniques a valid response with a good cost/benefit ratio.

In particular, satellite SAR interferometry is one of the latest techniques for the detection of Earth surface movements induced by natural and anthropogenic events, allowing to measure deformations over areas several tens of kilometres wide while retaining high precision and accuracy.

Differential Interferometric Synthetic Aperture Radar (DInSAR) represents a consolidated technique for the ground-deformation (Herrera et al., 2009; Tomás et al., 2011; Novellino et al., 2015; Confuorto et al., 2016; Tessitore et al., 2016; Di Martire et al., 2017) and man-made structures (dams, buildings, highways, bridges) monitoring (Di Martire et al., 2014; Infante et al., 2016; Nicodemo et al., 2016; Poreh et al., 2016; Tessitore et al., 2017). In detail, it allows to obtain time series of deformations covering the whole satellite acquisition period over a wide area and with a millimeter accuracy.

In the recent past, the use of DInSAR data for structural monitoring has been a key topic of current studies because it permits the detection of potential problems at different levels of representation with a consequent improvement of risk management and possible rehabilitations, so reducing costs and time of investigation (Infante et al., 2017).

The present work is devoted to analyze the potentiality of satellite-based techniques for structural health monitoring of an important infrastructure in Campania Region (Italy), which is interested along its linear development by several landslides, characterized by very-slow to slow kinematics.

Here, a general approach to investigate preliminary cause - effect relationship, as indicator of vulnerability of infrastructure affected by slow-moving landslides, has been provided.

Starting from regional scale to single sections of analysis, high resolution COSMO-SkyMed images allowed to investigate deformations along the whole road, identifying the most critical sections where a detailed field survey is required.

DInSAR data, integrated with geomorphological maps and field campaigns can help in the characterization of the stretches affected by active deformation which may require site-specific monitoring.

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2. THE APPROACH

In the present paper a general methodology for the assessment of behaviour of linear infrastructures prone to actions resulting from slope instabilities is developed, according to the flowchart shown in Figure 1.
Such approach was implemented in a GIS-semiautomatic routine to a preliminary analysis over large areas by creating easy-to-read map of anomalous (Meisina et al., 2008) sections of a linear infrastructure interacting with geological hazards.
Aimed to investigate preliminary cause-effect relationship between ground instability phenomena and infrastructure damage susceptibility, an integrated analysis of landslide geological and geomorphological settings and of field survey results is required.
Furthermore, to characterize landslide kinematics, its intensity can be considered: in particular, mean velocity of displacement, obtained through DInSAR processing, has been taken into account.
It is important to highlight that the acquisition of SAR images is affected by geometric and radiometric distortions, as a function of the incidence angle respect to the surface morphology. To this purpose, a pre-processing step is required to predict the feasibility of DInSAR technique over a certain area.
To estimate these effects, various techniques have been developed, which are based on the use of several images aimed to have different view angles. Starting from Digital Elevation Model (DEM) and geometric parameters of satellite orbit (incidence angle and orbit angle), the R-Index map (Notti et al., 2010, 2014) is generated to preliminary investigate the effect of topography on the presence of radar targets.
Subsequently, SAR image datasets acquired on “ascending” and “descending” tracks, processed by means of DInSAR technique, allow to obtain displacement velocity maps along the Line of Sight (LoS), as indicator of ground instability and of deformation of infrastructure surface.
The Coherent Pixel Technique (CPT, Mora et al., 2003), developed at the Remote Sensing Laboratory (RSLab) of Universitat Politecnica de Catalunya has been used to process satellite images: it is an algorithm able to extract from a stack of differential interferograms the deformation evolution during long time spans.
The cross-comparison of multi-temporal ground motion rates obtained by DInSAR data with local failures of involved structures recognized by in situ observations, permits to achieve the following main goals:
- identify “anomalous” sections classified as unstable;
- update available landslide inventory maps;
- assess spatial and temporal evolution of surface deformations.
As regards the identification of unstable areas, a “buffer” zone and inside it a “fishnet” grid have been created along the linear infrastructure identified from the available digital topographic map.
Subsequently, a displacement velocity threshold, discriminating stable from unstable targets, has been assessed: to such identification, a coefficient of variation, given by the ratio between the standard deviation and the velocity average module, for all selected scatterers, has been calculated.
The threshold value determined is about 2 mm/year, corresponding to a value for which standard deviation is higher than the mean velocity value (Colesanti et al., 2006).
Finally, comparison of velocity threshold value with the movement rate of each radar target identified inside the buffer zone provides the localization of moving pixels which can be considered unstable.
Aimed to a better understanding of the connection between predisposing landslide processes and deformations of the linear infrastructure, only pixels with at least the 50% of “moving” targets inside have been considered as unstable, allowing to identify points where similar displacement rate values tend to be clustered.
The above-mentioned steps are developed separately for analysis of interferometric data acquired along “ascending” and “descending” tracks and subsequently combined to achieve the final map of anomalous areas characterized by a high level of critical issues.
Moreover, available landslide inventory maps need to be not only accurate, but also periodically updated on a regular basis.
To this aim, DInSAR data, integrated with the information provided by a landslide inventory map and with the results of an accurate survey of damage to facilities, can provide a useful tool to update boundaries and state of activity of slow-moving landslides.
Indeed, landslide induced damage – whether recorded – can be considered as movement indicators and, thus, can be used to validate DInSAR products.
The two datasets are merged with an available landslide inventory map to investigate spatial and temporal evolution of ground instability phenomena and their progressive interaction with sections along linear infrastructure.
Moreover, it is important to note that the high density of measurement points and long-term coverage derived from the COSMO-SkyMed constellation provide valuable information to detect abnormal changes of displacement rates along infrastructure development.
The combination of interferometric data acquired along “ascending” and “descending” tracks, where available, allows to identify vertical and horizontal (East-West) components and prevalent direction of movement.

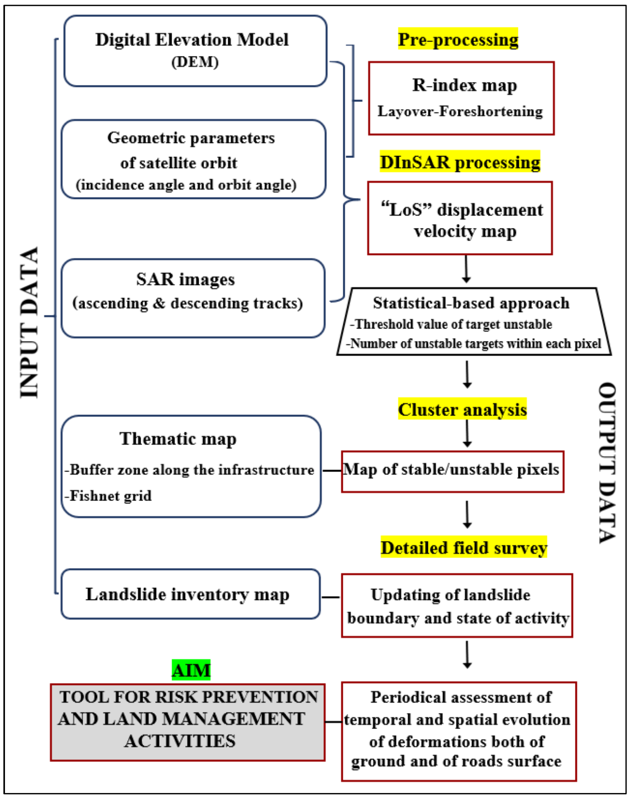

Figure 1. Flow chart of the procedure for linear infrastructure monitoring: input, output and main goals.

3. THE STUDY AREA AND AVAILABLE DATASETS

The proposed approach has been applied to control deformations of the National Road "S.S. 166", an important infrastructure in Campania Region (Italy), about 70 kilometres long, which is interested along its linear development by several landslides, characterized by very-slow to slow kinematics (Hydro-geomorphological Setting Plan of South Campania River Basin Authority, 2012).

Nine different villages are overpassed by the road: Capaccio Paestum, Roccadaspide, Castel San Lorenzo, Aquara, Bellosguardo, Roscigno, Corleto Monforte, San Rufo and San Pietro al Tanagro, all located East of Salerno (Fig. 2).

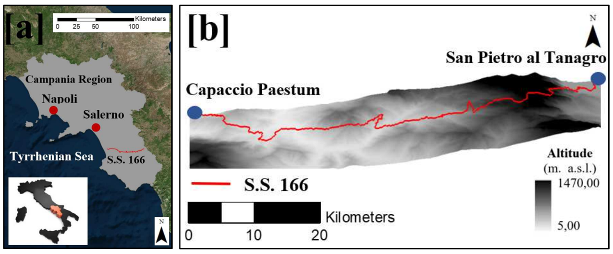

Figure 2. Location of "S.S. 166" linear infrastructure in Campania Region (a) and its referencing on a DEM (b).

The geological study area shows a variegated setting, both from a stratigraphic and a structural point of view.

The geo-structural aspect is related to the dynamics of Southern Apennines, the so-called fold and-thrust evolution, which developed between late Cretaceous and Pleistocene, because of the interaction between the European and African plates, and of the spreading of the Tyrrhenian oceanic basin (D'Argenio et al., 1975).

The geological and stratigraphic setting, cropping out along the road sector, is mostly made of flysch terrains, belonging to the Sicilide Unit (from Cretaceous to Miocene). This latter is a Structurally Complex Formation (Esu et al., 1977), with alternations and intercalations of sandstones, silts and limestones and including the so called Varicolored Clays Formation. These formations are very prone to weathering, making therefore such terrains very susceptible to instability phenomena.

According to the landslide inventory map provided by Hydro-geomorphological Setting Plan of South Campania River Basin Authority in 2012, 135 landslides have been surveyed along S.S. 166 and classified as complex, translational/ rotational slides, slow-moving flows and, in several cases, as areas affected by diffuse slow deformation (Fig. 3a).

As regards state of activity, in 2012 74 landslides were classified as active, 59 as dormant, and only 2 were identified as inactive (Fig. 3b).

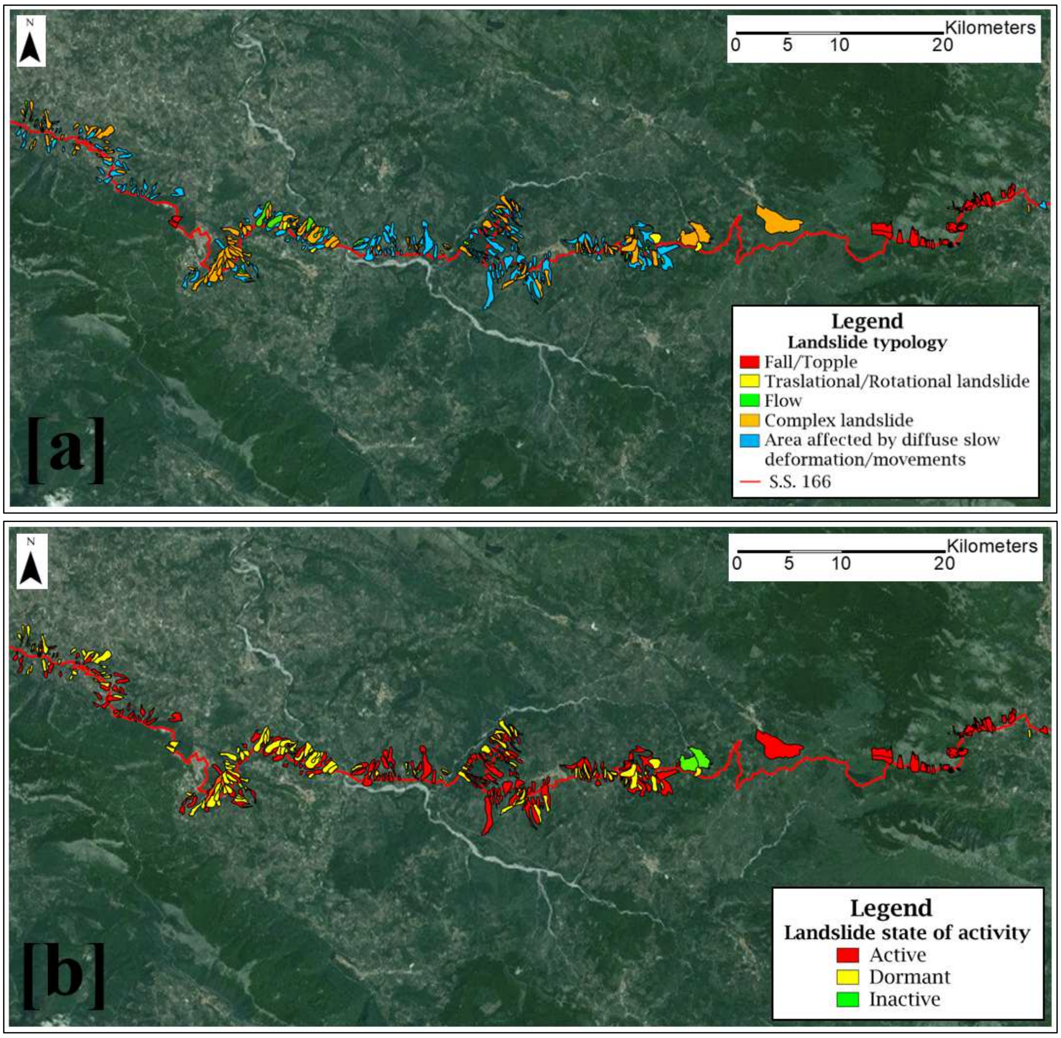

Figure 3. Landslide inventory map along "SS. 166": typology (a) and state of activity (b).

4. INTERFEROMETRIC PRODUCTS

As mentioned in section 2, according to the proposed approach, firstly the R-Index maps related to two different geometries have been generated to investigate the presence of radar targets along S.S. 166 (Figures 4a and 4b).

The maximum value of the R-Index, equal to 1, corresponding to the best geometry detectable by the satellite, has been obtained when the slope is parallel to the LoS. On the other hand, the smaller is the R-Index, the harder to detect a PS. In particular, if this value tends to 0, it means that the pixel is in foreshortening, while it will be in layover if R-Index results negative.

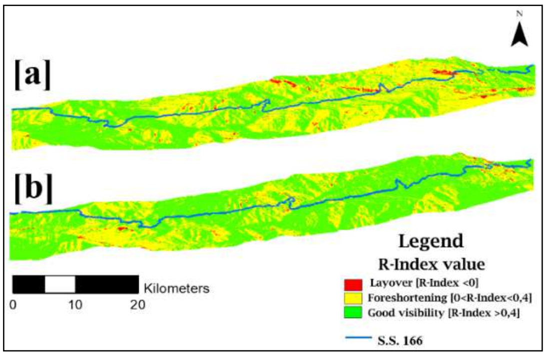

Figure 4. R-Index maps for ‘ascending’ (a) and ‘descending’ (b) tracks.

As it is possible to note in R-Index maps, a high density of pixels characterized by good quality can be obtained by ascending and descending datasets.

Furthermore, such preliminary analysis showed a visibility of the infrastructure in “descending” images higher than that obtained by “ascending” images.

In order to characterize landslide kinematics and to assess deformations of S.S. 166, 42 and 41 COSMO-SkyMed images, acquired respectively along “ascending” and “descending” track in time-span 2011-2014, have been processed by means of CPT (Mora et al., 2003).

The analysis has been carried out by exploiting the Temporal Sublook Coherence method for pixel selection, through the SUBSIDENCE processor, developed at the Universitat Politecnica de Catalunya of Barcelona.

Figure 5 shows deformation velocity maps along the satellite LoS direction obtained from the processing of COSMO-SkyMed SAR images in the period 2011-2014 along the whole S.S. 166.

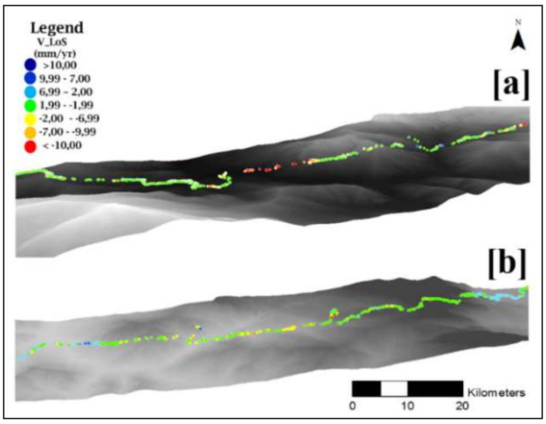

Figure 5. Maps of “LoS” displacement rate of targets identified along S.S. 166 in ‘ascending’ (a) and ‘descending' (b) orbit.

It is important to note that, aimed to define landslide intensity at ground level and to assess deformations of S.S. 166, a 50-m buffer-distance along the linear infrastructure has been created and only scatterers identified within such area have been considered (Fig. 6).

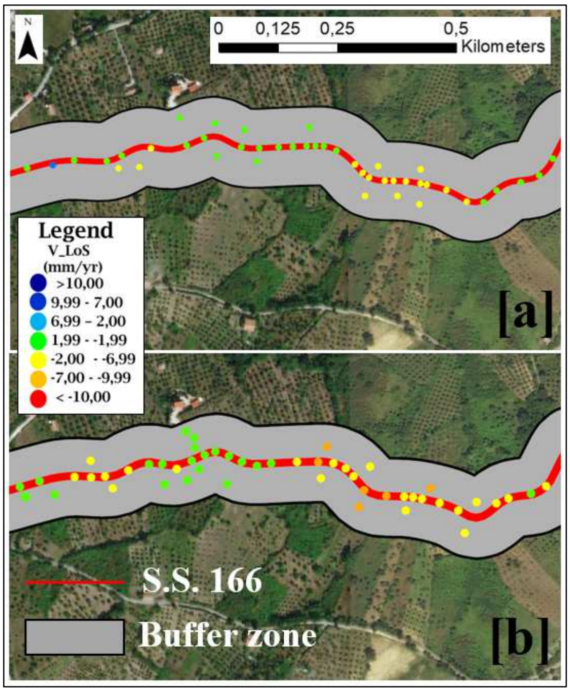

Figure 6. Example of “LoS” displacement velocity maps of targets identified into buffer zone along S.S. 166 by ‘ascending’ (a) and ‘descending' (b) image processing.

A high density of targets has been identified along the whole S.S. 166; moreover, the spatial ground resolution of each scatterer, resulting approximately 3 m × 3 m, allows a detailed investigation also at the scale of a single section deformation.

Finally, as it is possible to note, interferometric products confirm the occurrence of very slow and slow-moving phenomena, with velocities in the order of some mm/yr. In fact, maximum displacement rate in the above-mentioned time-span is about 20 mm/yr.

5. RESULTS AND DISCUSSION

Starting from distribution of targets identified along S.S. 166, clusters of moving pixels with velocities above a certain threshold, have been selected.

According to the proposed approach, a statistical analysis allowed to consider ± 2 mm/year as the appropriate threshold for the velocity, discriminating stable from unstable targets.

Furthermore, a fishnet inside the buffer zone was created with a pixel size of 50 m x 50 m, as to take into account spatial resolution of interferometric products and graphical error related to the working scale.

Finally, displacement rate of each scatterer has been compared with the defined threshold value of velocity: for a better assessment of occurring phenomena, exclusively pixels with at least 50% of “moving” targets inside have been considered as unstable.

“Ascending” and “descending” datasets have been separately analyzed and subsequently merged, thus providing a map of stable and unstable sections (Fig. 7).

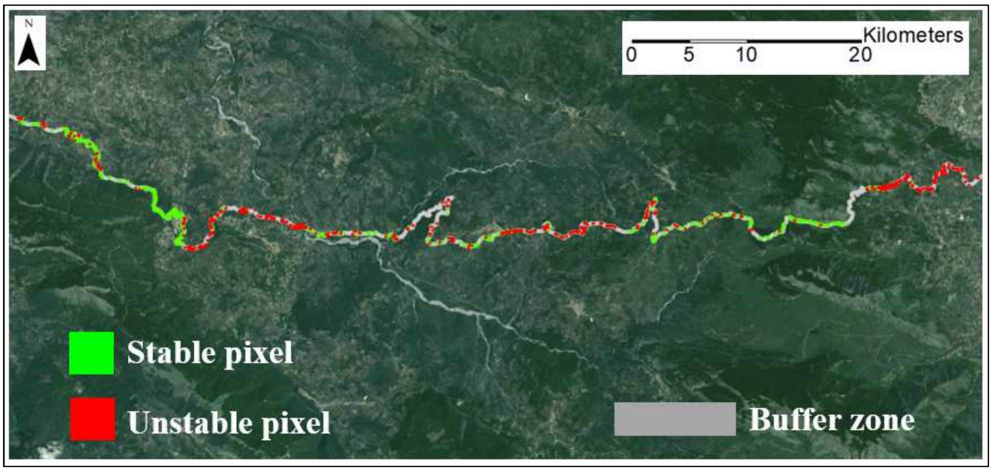

Figure 7. Map of stable/unstable pixels identified along S.S. 166.

Along S.S. 166, starting from available DInSAR data, 587 stable and 351 unstable pixels have been identified, thus highlighting the occurrence of movements in several sections of the road.

Map of stable/unstable pixels allowed to update landslide inventory map: the cross-comparison of DInSAR radar-interpreted data with the existing landslide inventory map and with damage surveyed along the whole road was performed, and landslide boundary and state of activity have been updated.

In the following, an example of landslide interesting S.S. 166 and updated by using interferometric products, is presented.

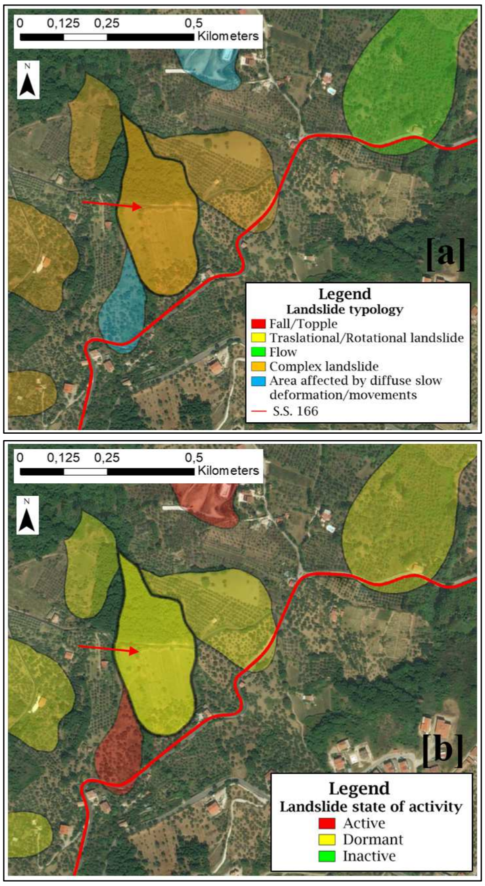

Figure 8. Excerpts of typology (a) and state of activity (b) inventory maps where the considered landslide is highlighted (marked line and red arrow).

In 2012, such landslide was classified by Hydro-geomorphological Setting Plan of South Campania River Basin Authority as a complex landslide, characterized by rotational and flow components. Furthermore, as regards state of activity, it was defined as dormant (Fig. 8).

Map of “anomalous” sections reported in Figure 7 showed the occurrence of unstable pixels in the surrounding area: moreover, field survey confirmed evidence of cracks on road near the considered landslide.

According to these reasons, landslide boundary has been updated assuming a retrogressive distribution of activity, whose rupture surface is extending in the opposite direction with respect to the movement direction (Fig. 9).

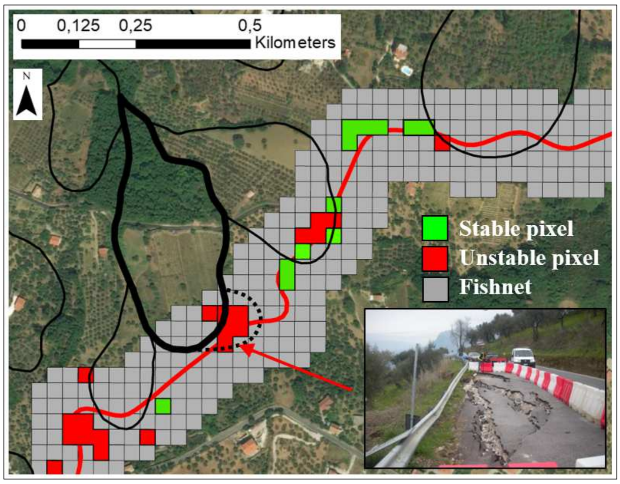

Figure 9. Combined use of map of the anomalous areas and results of field survey for updating of landslide boundary (black dotted line).

As regards state of activity, the availability of both ascending and descending data (Fig. 10) allowed to obtain vertical (V_Z) and horizontal (V_H) components of velocity (equations 1 and 2).

$$V_x = \frac{V_{asc} - V_z \times S_{zasc}}{S_{xasc}} \quad \text{(eq.1)}$$

$$V_z = \frac{V_{desc} \times S_{xasc} - V_{asc} \times S_{xdesc}}{S_{xasc} \times S_{zdesc} - S_{xdesc} \times S_{zasc}} \quad \text{(eq. 2)}$$

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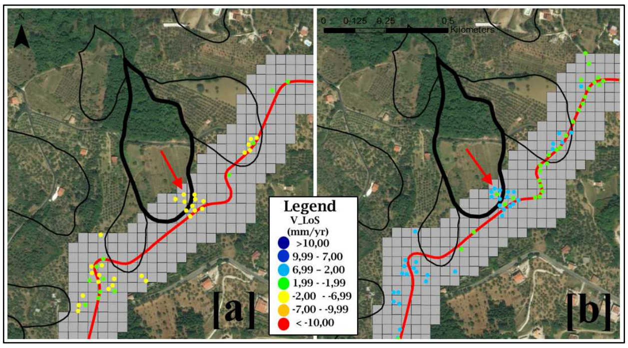

Figure 10. Targets identified by ascending (a) and descending (b) images within considered landslide.

Such analysis highlighted for scatterers identified inside the considered area, a displacement rate of about 5 and 12 mm/yr, respectively along vertical and horizontal direction, thus confirming the occurrence of damage to the road.

Finally, according to the above-mentioned results, such landslide, initially mapped as dormant, has been updated and re-classified as active.

The proposed methodology allows also to investigate spatial and temporal evolution of surface deformations, both of landslides and of infrastructure. In the following, an example of kinematic evolution assessment by using "anomalous" areas approach in another stretch of S.S. 166, is shown.

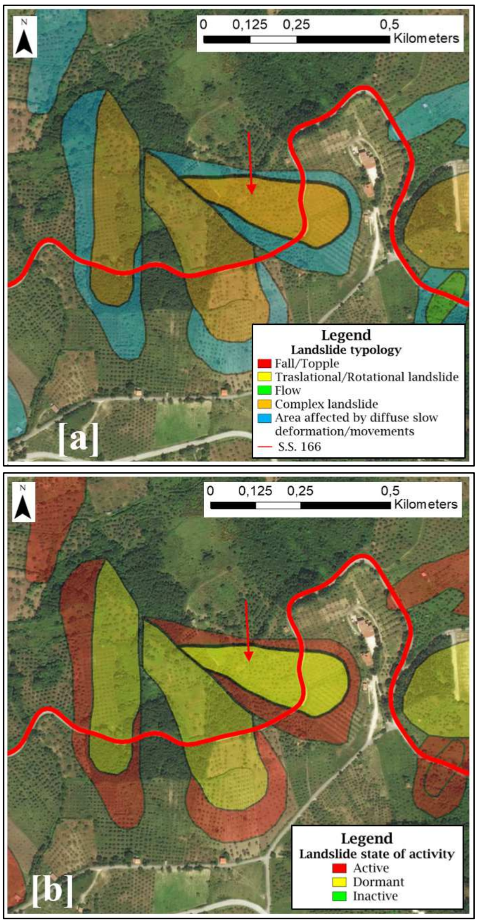

Figure 11. Excerpts of typology (a) and state of activity (b) inventory maps where the considered landslide is highlighted (marked line and red arrow).

The considered landslide has been identified as a complex landslide, while as regards state of activity, in 2012 it was classified as dormant by Hydro-geomorphological Setting Plan of South Campania River Basin Authority (Fig. 11).

Aimed to assess spatial and temporal evolution of surface deformations, the approach here proposed to identify "anomalous" areas has been applied with reference to each year of the considered time-span.

As a result, maps of stable/unstable pixels corresponding to displacement rates recorded by interferometric products in 2011, 2012, 2013 and 2014 respectively, have been obtained (Fig. 12).

As it is possible to note, starting from 2011 to 2014, unstable sections extend into both flanks of the considered area, thus identifying a progressive widening landslide (WP/WLI, 1993).

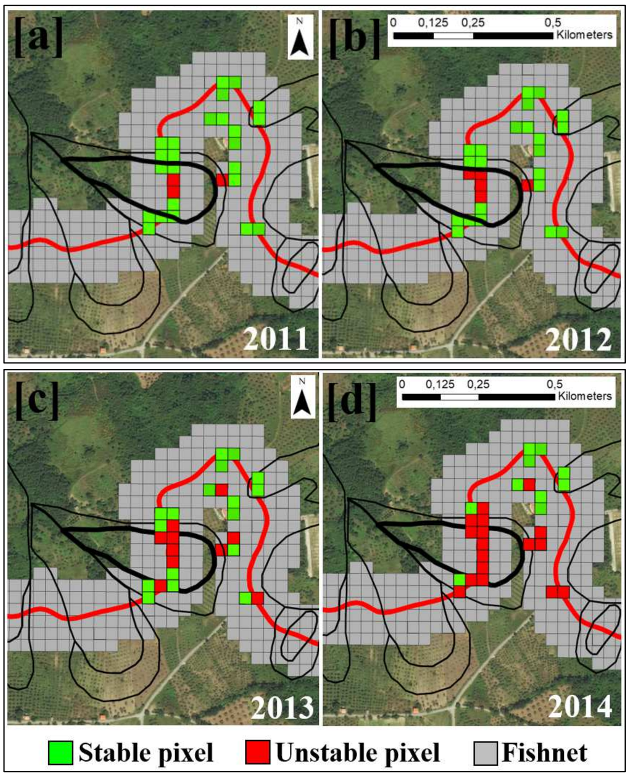

Figure 12. Excerpts of maps of stable/unstable pixels in 2011 (a), 2012 (b), 2013 (c) and 2014 (d).

Furthermore, the analysis of displacement time series of targets identified in such area both in "ascending" and "descending" datasets shows an increase of velocity in the period 2011-2014 and a progressive acceleration of ground movement (Fig 13), confirmed also by the occurrence of light damage to road surface (Fig. 14).

Target named "P1", identified within study area by "ascending" data, shows a "LoS" displacement rate of about 1 mm/yr in 2011, 4 mm/yr in 2012, 6 mm/yr in 2013 and 9 mm/yr in 2014; as regards "descending" dataset, target named "P2" shows a "LoS" displacement rate of about 1,5 mm/yr, 4 mm/yr, 6 mm/yr and 10 mm/yr, respectively in 2011, 2012, 2013 and 2014.

According to the above-mentioned results, such movement, showing significant velocities of targets identified both on ground and on road surface, can be again re-classified as active.

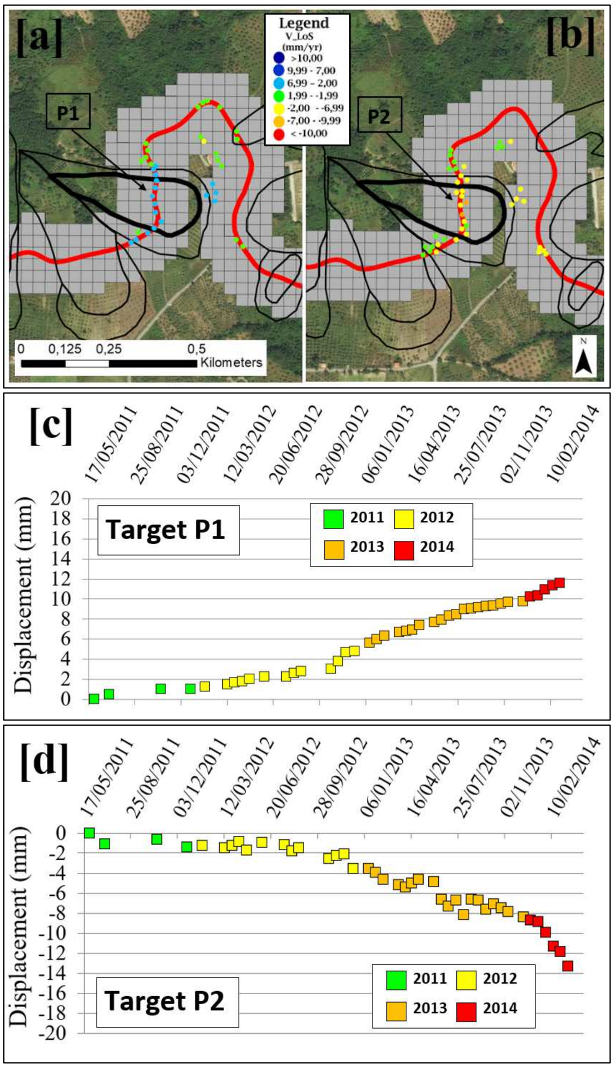

Figure 13. "LoS" displacement velocity maps and deformation time series of a target identified within the considered landslide, obtained by ascending (a, c) and descending (b, d) images.

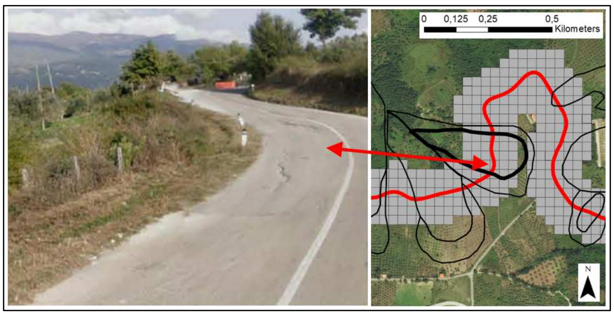

Figure 14. Damage surveyed along S.S. 166 within the considered area.

6. CONCLUSIONS

The present work has showed some possible useful analyses of DInSAR data for deformation monitoring of a linear infrastructure in Campania Region (Italy).

DInSAR technique is of great potential value to utility companies willing to monitor assets in near real-time, and could ultimately lead to observations of an entire infrastructure network with a high spatial and temporal resolution.

The proposed approach, implemented in a GIS-semiautomatic routine, uses as input data Digital Elevation Model (DEM), SAR images, geometric parameters of satellite orbit and available landslide inventory maps, coupled with geomorphological field survey and geological characterization of the considered area. It can help in the identification of stretches and sections along linear infrastructures affected by active deformations which may require site-specific monitoring, provides information on spatial and temporal evolution of deformations, allows periodically to update boundary and state of activity of ground instability phenomena.

To this purpose, it represents a very fast tool, which permits, in a preliminary analysis, to reduce costs and time of investigation. High spatial and temporal resolution of SAR images allow, nowadays, to develop a quasi-real time monitoring, investigating deformations and structural behaviour of large areas and single parts of an infrastructure. In situ investigations combining more adequate and higher-resolution SAR data with ground references may provide a very precise monitoring system.

Such kind of studies can improve the knowledge of DInSAR tool and demonstrate their applicability to structural monitoring. This, in turn, represents a key topic of current researches aimed to detect potential problems to the improvement of risk management and possible rehabilitations.

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