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LANDSLIDE MONITORING AT BOTH LARGE AND DETAILED SCALES USING SATELLITE A-DINSAR IN SOUTHERN LAZIO (ITALY)

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EXTENDED ABSTRACT

L'utilizzo di grandi stack di immagini SAR (Synthetic Aperture Radar) satellitari, analizzati con tecniche di interferometria differenziale avanzata (A-DInSAR), si è dimostrato, altamente efficace per lo studio dei fenomeni franosi lenti, per caratterizzarne lo stato di attività e il comportamento cinematico e analizzarne l'impatto sulle infrastrutture. Tale tecnica consente la ricostruzione delle serie temporali di spostamento dei punti di misura e di monitorare il territorio su scala regionale, fornendo grandi volumi di informazioni che generalmente non possono essere analizzate efficientemente e in tempi brevi, tramite interpretazione o analisi guidata da giudizio esperto. Negli ultimi anni, diversi studi si sono concentrati sull'automazione di parte del processo di post-elaborazione, per identificare le aree soggette a deformazione dalle mappe di velocità A-DInSAR. Questo lavoro ha avuto il duplice scopo di estrarre in modo semi-automatico informazioni sulle zone in deformazione (qui denominate AOIs o aree di interesse) da grandi quantità di dati su vaste aree, e di mostrare come ottimizzare i dati di spostamento multi-sorgente A-DInSAR in analisi a scala di versante, utilizzando misure di velocità A-DInSAR multi-sensore, evidenze geomorfologiche, e informazioni su eventuali danni a edifici o infrastrutture. Gli effetti visibili sull'edificato, insieme alle caratteristiche geomorfologiche dei versanti soggetti a movimento, consentono di verificare e mettere in relazione la distribuzione e il livello del danneggiamento con la cinematica e l'evoluzione del movimento di frana, allo scopo di proporre l'aggiornamento dell'inventario delle frane, con modifiche sia in termini di perimetro che di stato di attività.

In questo contributo, viene fornita una breve panoramica generale del metodo utilizzato per l'analisi a scala regionale, e un approfondimento a scala di versante su tre casi studio, situati nella provincia di Frosinone (Italia centrale), presso i comuni di Belmonte Castello, Strangolagalli e Arpino. Tali casi riguardano frane a lento movimento, quali meccanismi complessi o di roto-traslazione, poco profonde o superficiali, che presentano interferenza con strade e zone abitate.

La sequenza di passaggi utilizzata nell'analisi a scala di versante parte dal livello informativo di riferimento comune, ovvero le mappe di velocità LOS (*Line of Sight*) di Sentinel-1 (in banda C, immagini dal 2015 al 2021), da tecnica PSI (Persistent Scatterers Interferometry). Al fine di ottenere una maggiore densità di punti di misura, sono state elaborate tali mappe anche con dati COSMO-SkyMed* in banda X (immagini dal 2010 al 2022) con risoluzione spaziale più elevata (3 m × 3 m). Grazie alla maggiore risoluzione spaziale fornita dai dati COSMO-SkyMed e grazie alla fotointerpretazione e all'utilizzo di un DEM ad alta risoluzione (5 o 10 m), l'estensione delle aree soggette a deformazione può essere definita e mappata preliminarmente con un buon livello di dettaglio. Tale mappatura preliminare è necessaria per guidare i rilievi di sito, che comprendono sia (*i*) un'analisi geomorfologica, sia (*ii*) un rilievo del livello di danneggiamento degli edifici e delle infrastrutture. Entrambe le indagini contribuiscono alla valutazione della corrispondenza tra aree interessate da movimento (AOIs) e processi franosi di prima o di seconda generazione. I risultati presentati hanno evidenziato che i big data A-DInSAR gestiti in modo semi-automatico a grande scala e analizzati integrando diversi dati ancillari a scala di versante, sono uno strumento maneggevole e efficace per fornire un aggiornamento dello stato delle conoscenze sui movimenti attivi dei versanti, di grande utilità per le autorità locali incaricate della mitigazione del rischio frane.

Questo studio è stato sviluppato nell'ambito di un accordo istituzionale tra il Servizio Geologico e Sismico della Regione Lazio (Italia) e il Centro di Ricerca sulla Previsione, Prevenzione e Mitigazione dei Rischi Geologici (CERI), focalizzato sul monitoraggio dei processi di deformazione del suolo nel territorio amministrativo del Lazio mediante interferometria satellitare avanzata.
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ABSTRACT

The specific aim of this work has been exploiting satellite Advanced Differential SAR Interferometry (A-DInSAR) big data through the implementation of methodologies that can provide new insights into the identification of unknown landslides and the update of the inventoried landslides, at two different levels of detail: regional and slope scales. In particular, the slope-scale studies are aimed at investigating the landslide processes that pose the greater risk of interfering with roads and inhabited zones, using both multisource A-DInSAR velocity measurements, geomorphological evidence, and surveys of damage to buildings or infrastructure. This multiparametric evaluation allows the update of the state and styles of activity and the landslide perimeters. In this paper, we provide a general overview of the method that works for regional scale analysis, with a focus on 3 case studies located in the Frosinone province (Central Italy), that have been investigated at a slope scale. Such cases concern slow-moving landslides such as complex, slow flow, or roto-translation mechanisms, featured by shallow or moderate depth and extension. The presented results pointed out that A-DInSAR big data can provide an update of the state of knowledge of active slope movements at a regional scale and can drive detailed studies with high-resolution data and on-site surveys to assess the hazard scenarios.

Keywords: *slow-moving landslides, damage to the buildings, satellite interferometry, landslides inventory update.*

INTRODUCTION

Nowadays, satellite SAR interferometry techniques are commonly exploited for landslide characterization, mapping, and monitoring, and for back analysis studies. Advanced Differential SAR Interferometry (A-DInSAR) techniques that use large data stacks of images, allow reconstruction of the time series of displacement of the measurement points with the capability to monitor the territory at the regional scale. Advanced differential interferometry synthetic aperture radar (A-DInSAR) techniques (Ferretti *et alii*, 2001; Berardino *et alii*, 2002) have proven to be highly suitable for investigating slow-moving phenomena, representing an efficient methodology for characterizing the state of activity and the kinematic behavior (e.g., Antonielli *et alii*, 2019; AO *et alii*, 2020; Mondini *et alii*, 2021) and analyze the impact on infrastructures (e.g., Nobile *et alii*., 2018; Peduto *et alii,* 2021; Cignetti *et alii*, 2023).

Since 2022, the Copernicus European Ground Motion Service (EGMS) has implemented Sentinel-1 data into high-resolution ground motion maps of the whole European continent, freely available. However, the outputs consist of a map of displacement over millions of points, for each of which a displacement time series is obtained, providing a large volumes of information that generally cannot be quickly or easily analyzed at a regional scale (Barra *et alii*, 2017). In recent years, several studies focused on automating some parts of the post-processing analysis process to identify deforming areas from A-DInSAR velocity maps (*e.g.*, Solari *et alii*, 2018; Festa *et alii*, 2022). This work aims to semi-automatically extract information from massive data over large areas for advisory purposes and inventory update perspectives, and also shows how to optimize A-DInSAR multi-source displacement data through the integration of field observations for slope-scale analysis to define the impact of a slope movement on the anthropic structures. The visible effects (*i.e.*, crack pattern and width) on the exposed buildings, along with the geomorphological features of the studied slopes allowed for checking the distribution of damage severity (affecting both buildings and infrastructures) concerning the kinematics of the landslide. The level of knowledge obtained on the analyzed landslides can be used effectively to manage landslide risk in the short term and is useful to describe the current landslide displacement style. The update of the landslide inventory has been proposed for the selected case studies, with changes in terms of both perimeter and state of activity.

This study has been developed in the frame of an institutional agreement between the Geological and Seismic Service of Lazio Region (Italy) and the Research Centre on Prediction, Prevention, and Mitigation of Geological Risks (CERI), focused on the monitoring of ground deformation processes in the Lazio administrative territory through advanced satellite interferometry.

MATERIALS AND METHODS

This study developed at two different scales of analysis: 1) regional scale (Frosinone province and a minor part of the Roma province), with the implementation of a semi-automatic procedure for identifying landslide candidates in the Sentinel-1 maps of velocity of displacement provided by EGMS service, and ranking in terms of the process intensity (area and velocity), as a proxy of hazard, considering also the intersection with urbanized areas and infrastructures; 2) slope scale focus, based on a more detailed analysis of COSMO-SkyMed datasets and through the integration of different data with in-situ geomorphological survey.

Regional-scale semi-automatic methodology

The satellite interferometric data was obtained with the A-DInSAR technique, for both acquisition geometries (ascending and descending) of the Sentinel-1 constellation, released by the European Ground Motion Service (EGMS) project (https://land.copernicus.eu/pan-european/european-ground-motion-service). The analysis exploits the BASIC products, that contain movement data measured along the Line of Sight (LOS) of the Sentinel-1 satellite and referred to a local reference point. Such data consist of the velocity of displacement maps (ascending and descending) of the study area, represented by millions of persistent scatterers (PSs). Regarding the study area, the PS coverage can be estimated as corresponding to 22% of the territory. Raster maps have been developed that interpolate the velocity values (the so-called "heatmaps") to identify the moving clusters of measurement points, with a velocity greater than ± 2 mm/year. These clusters represent areas of ground deformation potentially related to landslide processes of various mechanisms and extents. Only areas with a slope > 5° were considered to minimize errors deriving from this selection, in which the recorded movements can realistically be attributable to gravitational phenomena. To group the moving areas linked to the same or adjacent landslide processes, the areas located within a maximum distance of 200 m were grouped into clusters. The envelope of the clusters thus identified was designed to delimit the areas considered as landslide candidates, here called "areas of interest" (AOIs), where geomorphological validation and, eventually, slope-scale analysis, also based on field survey, have been detailly conducted.

Slope-scale analysis

Some of the sites affected by deformation (AOIs), identified with the regional-scale analysis, were investigated in more detail through an approach specifically developed to optimize the information from satellite multi-source interferometry and in situ surveys. The final purpose of this analysis concerned an integrated study to investigate the size, mechanism, and kinematics of some selected landslides. For selected AOIs, the interference (in terms of damage severity distribution) with the infrastructures and the built environment was also investigated.

The case studies here described include AOIs inventoried in three different municipalities of the Frosinone province (Central Italy): Belmonte Castello, Strangolagalli, and Arpino.

The sequence of steps used in this approach starts from the common reference information layer, that is the LOS velocity maps of Sentinel-1, and as a first step, it involves the achievement of more detailed velocity measurements, using COSMO-SkyMed data from 2010 to 2022, that benefit of higher spatial resolution (3 m × 3 m, while the Sentinel-1 geometric resolution is 20 m × 5 m). The latter can provide results with a higher density of measurement points in areas, where natural persistent scatterers exist (especially buildings or infrastructures).

The extension of the areas subject to deformation can thus be better defined and mapped in a preliminary way using photointerpretation and analysis of a hight resolution DEM (5 or 10 m), to guide the on-site "ground truth" acquisition, and validate the remote analysis. In particular, features like main and secondary scarps, morphological terraces, and concave-convex longitudinal or concave transversal profiles have been identified. The on-site activities include two different kinds of surveys: (*i*) a geomorphological analysis, to identify and verify key indicators of the landslide presence, and (*ii*) a survey of the level of damage to buildings and infrastructures. Both surveys contribute to the evaluation of the possible correspondence between areas affected by movement (AOIs) and first-time failure or second-generation landslide processes (*i.e.* reactivations).

The detection of the damage occuring in buildings was concurrently carried out qualitatively, based on expeditious observations of the crack patterns potentially correlated to the investigated landslides, following the procedure proposed by Burland *et alii* (1977). For this case study, the attribution of a class of damage was based on the opening of the cracks. In particular, Burland's (1977) classification is divided into six damage classes (D0: negligible, D1: very slight, D2: slight, D3: moderate, D4: severe, and D5: very severe) based on the width of cracks (related only to visible cracks or esthetic damage). Within these classes, the measurements of the widths of the cracks are approximate. Both average and maximum values of damage have been considered for each involved building.

GEOLOGICAL SETTING OF THE CASE STUDIES

The pilot study area included the entire province of Frosinone and also seven municipalities bordering it to the northwest, belonging to Rome's province. It is located in the central Apennines, specifically, the Latium-Abruzzi Apennines orogenic system, between the Simbruini Mountains-Ernici Mountains alignments and the Lepini Mountains-Ausoni ridges structure, separated by the Valle Latina (Amodio & Bovina, 2002). The Valle Latina spans approximately 120 km in length and 15 km in width. The local stratigraphic succession displays units of a Meso-Cenozoic carbonate platform that is more than 3 km thick. This platform is covered by Upper Miocene-Pliocene terrigenous deposits, which represent the foreland basin of the Apennine chain (Fabbi, 2018). The sedimentary formation is composed of hemipelagic deposits from the 'Marne ad Orbulina' Formation and turbiditic sediments associated with the Frosinone Formation (Tortonian-Messinian) (Centamore *et alii*, 2010), indicating its involvement in the foreland area (Angelucci, 1966; Angelucci *et alii*, 1979). Continental and volcanic deposits, such as Middle Pleistocene fluvio-lacustrine deposits and terraced alluvium, are also present in the area (Fig. 1).

The territory of Belmonte Castello encompasses Lower Cretaceous-Dogger dolomitic limestones. To the east, the valley floor holds alluvial soils, primarily sandy silts with gravels and sands. The eastern slope of Belmonte exhibits marly-arenaceous terrigenous facies, predominantly clayey, from the pelitic-arenaceous association of the Frosinone Formation. Landslides predominantly affect these lithologies.

In the study area of Strangolagalli the geological landscape is notably homogenous. The settlement primarily rests on the graded arenaceous clayey complex associated with the Frosinone Fm. Strangolagalli can be divided into three distinct sectors: a northern region rich in alluvial deposits and some volcanic outcrops, a central

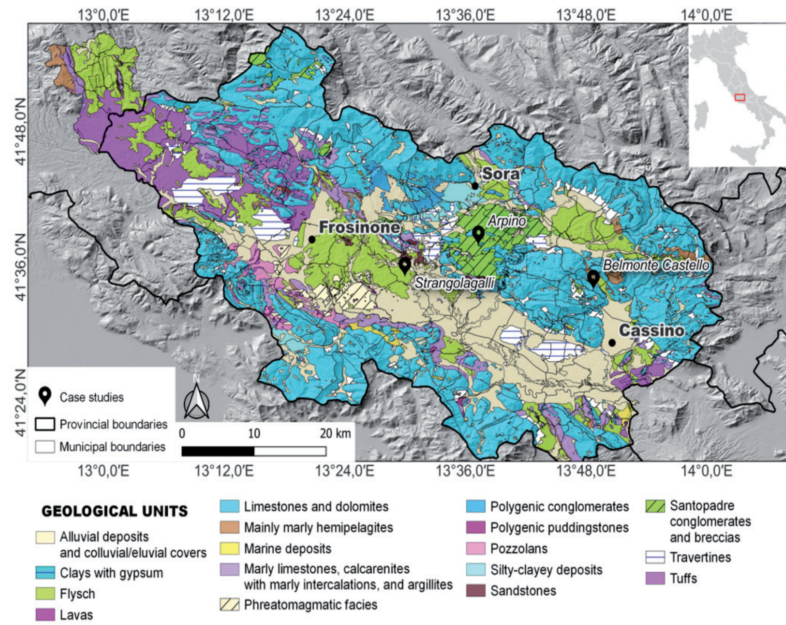

Fig. 1 - Geological map of the study area, modified from the 1:25.000 scale geological map of the Lazio Region (Cosentino et alii, 2012)

zone predominantly featuring flyschoid material, and a southern area with limited alluvial cover from the Liri River. Notably, the central zone faces significant gravitational events due to the erodibility of the flysch, leading to numerous rotational/translational slides, well-documented in the Italian Landslide Inventory (IFFI) by ISPRA (Trigila *et alii*, 2007; Trigila *et alii,* 2018).

The Santopadre Conglomerates Formation dominates the study area of Arpino, comprising two distinct members. The lower member consists of laminated siltstone, clayey sandstones, and yellowish well-cemented calcarenites. It suggests a consistent fluvial-lacustrine depositional setting. The upper member, positioned atop the lower one through an erosional surface, primarily comprises gravels and sands with subordinate pelitic lithofacies (Carrara & Giraudi, 1995). Landslide occurrences are significant in specific mountainous and hilly areas within the municipal territory. Steep rocky slopes and the southern slopes of the historic center present rockfall phenomena, threatening the roads below.

RESULTS

Regional-scale results

The mean velocity map of ground movement along the LOS derived from the Sentinel-1 satellite, in the period between 2015 and 2021 has been converted into the corresponding heatmaps (in both acquisition geometries, the ascending one is shown in Fig. 2). The total number of retrieved AOIs is 641 in ascending Sentinel-1 geometry and 704 in descending Sentinel-1 geometry. 56 of these AOIs have been detected in both ascending and descending geometries, so the AOIs are overall 1289 in the test area, which included the province of Frosinone and 8 municipalities belonging to Rome's province (Fig. 3a).

The possible occurrence of inventoried landslides polygon (from the PAI and/or from the IFFI catalogs) concurrently with the AOIs has been verified: about 26% of the AOIs intersect a PAI (Autorità di Bacino distrettuale dell'appennino Meridionale, 2018) inventoried polygon, and only 12% intersect an IFFI inventoried polygon. This means that the results of this study greatly expand the knowledge about active deformation in large-scale analysis, identifying minor slope movements.

The result of this procedure has been verified by expert judgment, to discard possible outliers that can represent local disturbances, other effects, or deformation phenomena that cannot be linked to landslides.

The scatterplot distribution (log (Area) vs maximum velocity) of the AOIs inventoried within the study area, from ascending and descending Sentinel-1 datasets are reported in Fig. 3b. About 80% of the AOIs show small dimensions (with an area between 0.0001 and 0.01 km^2) and low displacement velocities ranging from 2 and 3 mm/yr. Some of the AOIs located in the upper-right part of the scatterplot (with high velocity and relatively large dimension) were selected for the slope-scale analysis, through an in-situ geomorphological survey and building damage inspection. In particular, the slope analysis concerns slow processes that involve large portions of the slope that interfere with inhabited areas, crops, and roads of regional importance.

Slope-scale results

In this section, the results achieved in Belmonte Castello, Arpino, and Strangolagalli municipalities are shown: for each case study, the Sentinel-1 interferometric products, from 2015 to 2021, allowed to identify the location and the velocity of the deformation areas, and the A-DInSAR analysis with COSMO-SkyMed images provided an upgrade of the density of measurements, and therefore a greater detail to analyze the areas affected by slope deformation. Moreover, the main results of the on-site surveys for the three case studies will be described.

Belmonte Castello

Although a large part of the study area of Belmonte Castello is characterized by crops and vegetation, and the total number of PSs detected on the slope is low, the LOS velocity maps of Sentinel-1 highlighted some clusters of moving points (Fig. 4a) which have been grouped in four AOIs (blue polygons in Fig. 5).

Three main clusters of unstable PSs are located respectively in the detachment area (north-eastern part of the slope, at Spetina locality), in the central sector (corresponding to the Scarpatosta locality), and in the downstream area (in the south-western part, at Cretone locality; Fig. 4a). The greatest displacement rates were identified in the central part of the slope, with a maximum velocity of displacement of about 10 mm/year both for the ascending geometry and for the descending geometry indicating a movement predominantly horizontal in a westward direction (consistent with a downslope movement).

The field survey and the A-DInSAR data allowed the identification of three landslide bodies (called L1, L2, and L3) with different typologies and kinematics, mapped at a scale of 1:5.000 (Fig. 5). The northernmost landslide process (L3) is represented by a rockfall, with a visible detachment zone located at the top of

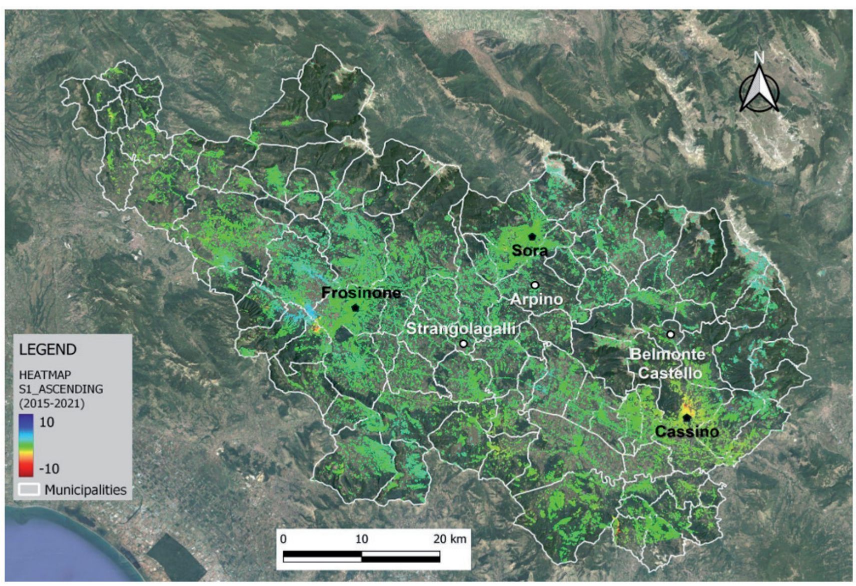

Fig. 2 - Heatmap of the mean velocity values along the LOS (ascending) of the Sentinel-1 satellite, in the time period 2015-2021

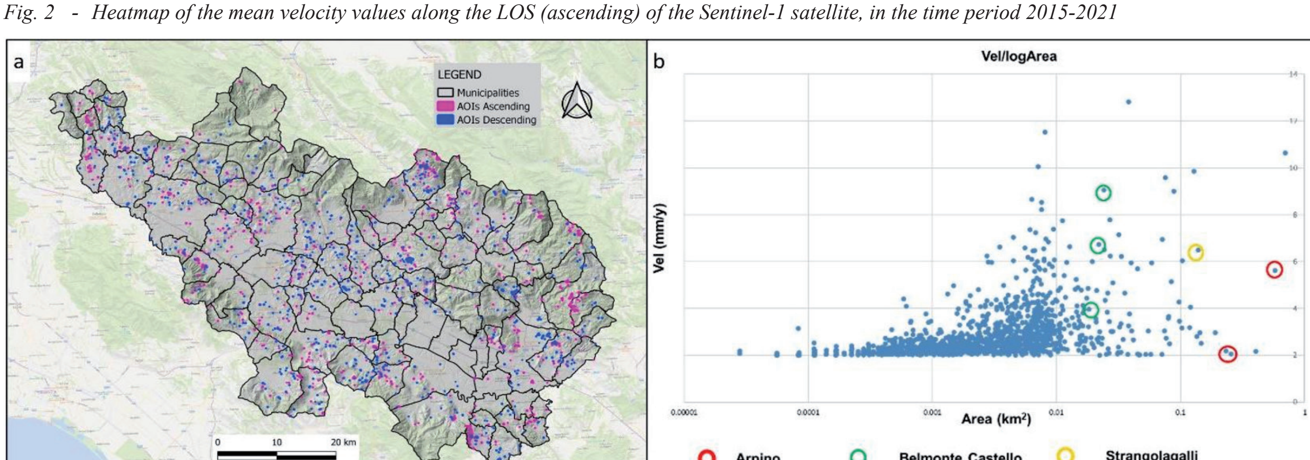

Fig. 3 - a) AOIs distribution within the study area, including the Frosinone province and 8 municipalities belonging to the Rome province. b) Scatterplot distribution (log (Area) vs maximum velocity) of the AOIs inventoried within the study area, from ascending and descending Sentinel-1 datasets. The highlighted points represent the selected case studies (AOIs both ascending and descending) described through the slope-scale analysis

the slope, and the corresponding accumulation zone of limestone blocks, where the limestones belonging to the Lazio-Abruzzo Series crop out. The central and downstream parts of the slope are characterized by altered flysch with prevalent pelitic components. Here, the slope is affected by two roto-translational landslides (L1 and L2) with slow kinematics that show typical scarps and three orders of terraces. The lateral limits of the landslide are represented by streams or incised valleys which, eroding the landslide body laterally, generate secondary instabilities.

Considering the existing landslide inventory, *i.e.* PAI and IFFI, only the north-eastern part of the slope, corresponding to about 30% of the mapped landslide, is included in the catalog, within a "very high hazard" zone (P4), which is considered as "potentially affected by landslide triggering, transit, and invasion phenomena with expected high intensity" (PAI; Fig. 4a), while the landslide process is not mapped in the IFFI catalog. As for the damage, the available dataset resulted from surveys carried out in the summer of 2023 over the entire slope area, and the damage severity levels of the surveyed buildings were classified according to Burland *et alii* (1977). In total, 144 artifacts were surveyed in the field activities for the area of Belmonte Castello. The map in Figure 5 shows the anthropic structures (mainly buildings and retaining walls) to which the damage class has been attributed. Several cracks on the facades have been observed throughout the study area, with a greater concentration in the NE sector, close to the main scarp (Fig. 4b and c): the interaction between slope instabilities and buildings was found near the locality of Spetina, where a maximum severity of the damage (D5) has been assigned to one of the residential buildings (Fig. 4b). The largest deformations along the road network were surveyed in Via Spetina, Via Coltroni, Via Scarpatosta (Fig. 4d and e).

Strangolagalli

The study area is located in the northwestern part of the municipality of Strangolagalli, which presents a complex hilly morphology, where eluvial colluvial deposits which stand above an arenaceous slope-dipping flysh, crop out. Three landslide bodies, with different transport directions, towards the north and northeast, can be recognized by the on-site observations. The larger one is characterized by a morphologically concave area with a subcircular shape, and it includes maximum velocity values between 6 and 10 mm/year in both Sentinel-1 and COSMO-SkyMed datasets. The velocities along the LOS vary within the area affected by displacement up to more than 10 mm/year (direction away from the satellite in descending geometry; Fig. 6a). The latter shows a high density of PSs that precisely mark the extension and perimeters of the moving areas, allowing an update of the preexisting landslides perimeters of the PAI inventory (Fig. 6b). The analysis of the time series has allowed us to reconstruct the evolution of the movement revealing that from 2010, the slow displacement tends to reduce the velocity until January 2018, when a sharp increase in velocity indicates reactivation of the slope movement that is probably still underway. Extensive cracks occur in neighboring buildings (Fig. 7b-e), with a level of damage from moderate to serious, proving an active movement of the slope. The very good spatial correlation between the damaged buildings and the area with moving PSs highlights the intensity of the process and remarks the resulting risk.

The other two landslide processes mapped in PAI catalogs are located in the northwestern part of the study area (Fig. 7a), where clear geomorphological evidence has been revealed by the field survey. These processes show a movement directed to the North. As the satellite acquisition geometry cannot detect measurements in a north-south direction, only the vertical component of the

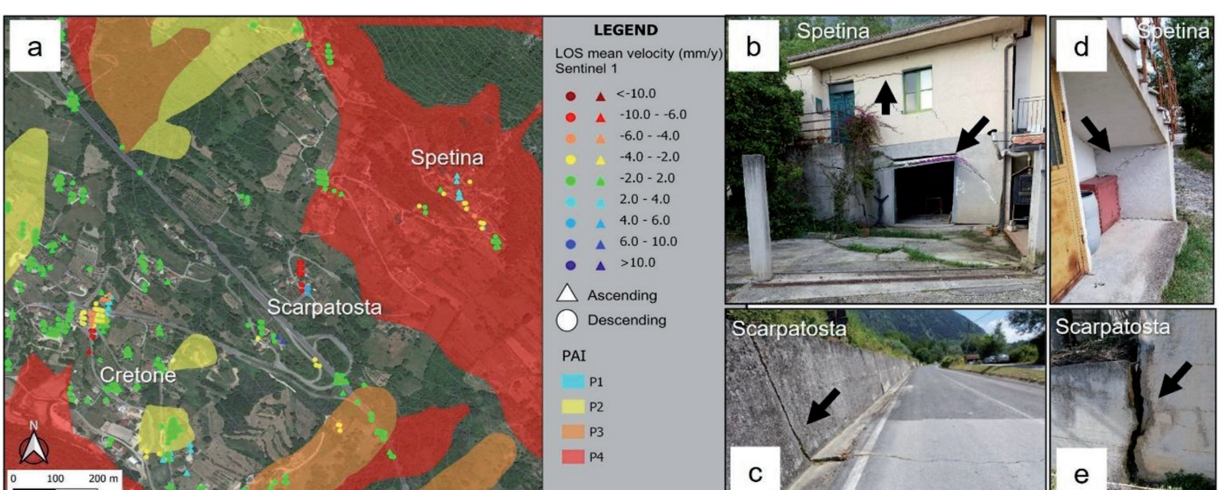

Fig. 4 - a) Sentinel-1 LOS velocity map (descending and ascending), with inventoried landslides from the PAI catalog, in the Belmonte Castello municipality; PAI classes: P1: moderate hazard; P2: medium hazard; P3: high hazard; P4: very high hazard; b, c, d, e) photographs of the cracks on the most damaged buildings roads, and walls

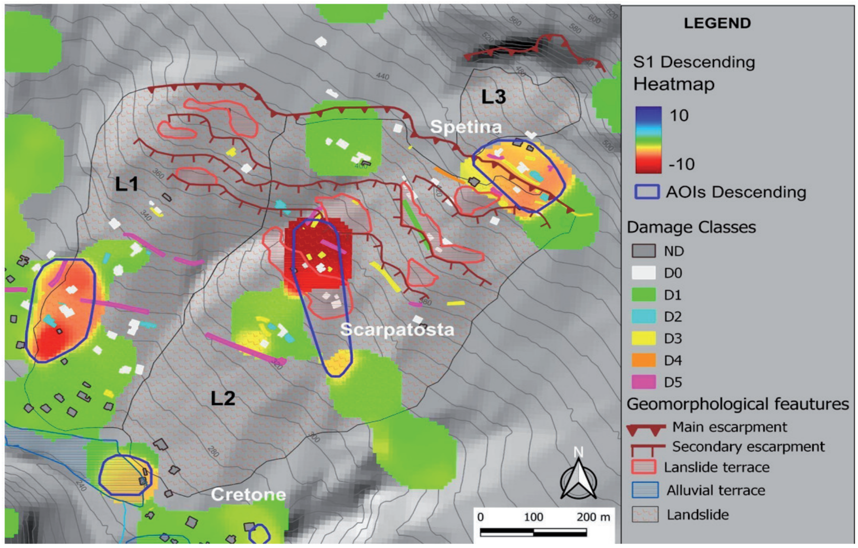

Fig. 5 - Sentinel-1 heatmap (descending) and AOIs in the Belmonte Castello area. The landslide perimeters L1, L2, and L3 defined by this work have been represented in grey; damage classes of the surveyed buildings and walls are ND= not defined; D0= negligible, D1= very slight, D2= slight, D3= moderate, D4= severe, and D5= very severe

deformation can be measured here. The COSMO-SkyMed velocity values (between 2 and 4 mm/year) show that the northern area underwent a slow displacement, with a vertical component of movement. This suggests that the landslide is retreating upstream and that the landslide processes have a rotational style and much larger dimension than those outlined in the inventories (tentative landslide perimeter in white in Fig. 7a).

Arpino

These AOIs are located south of the center of the town Arpino and involve a zone extending 1.5 km by 800 m, with a very complex topography, that concerns a slope dipping to the west/north-west with a rather gentle slope and several deeply incised gullies. Here, a loose conglomerate in a sandy-silty matrix, with intercalations of sand and organic silts (the Plio-Pleistocene Santopadre Formation) crop out.

The displacement velocity maps from COSMO-SkyMed data provide a greater density of measurement points, showing how the velocities vary within the area affected by displacement up to more than 10 mm/year in the west direction approximately (Fig 8a and b). These intense displacement rates cause visible evidence on the slope and the buildings. The area is extensively anthropized and cultivated, therefore the geomorphological evidence of landslides is more difficult to observe. On the contrary, the damage to buildings, walls, and roads is well recognizable and often consists of persistent cracks open up to 25 mm (Fig. 9b and d). At least 33 buildings (mostly residential) show moderate to serious damage, and some of them are located in areas not included by the known landslides of the PAI or IFFI catalogs.

As emerged from the work of Amodio & Bovina (2002), these landslide phenomena are characterized by detachment

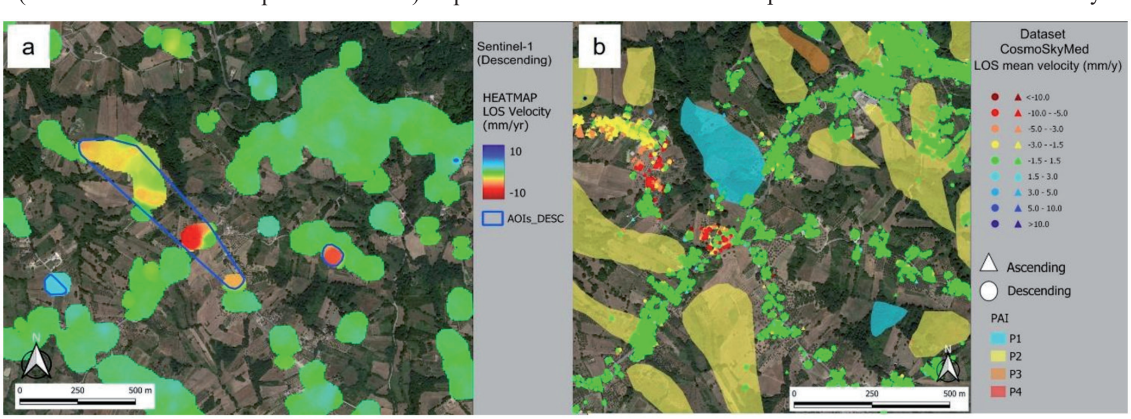

Fig. 6 - A-DInSAR results in the Strangolagalli municipality; a) Sentinel-1 heatmap (descending) and AOI automatic identification; b) COSMO-SkyMed LOS velocity map (both ascending and descending), with inventoried landslides from PAI catalog

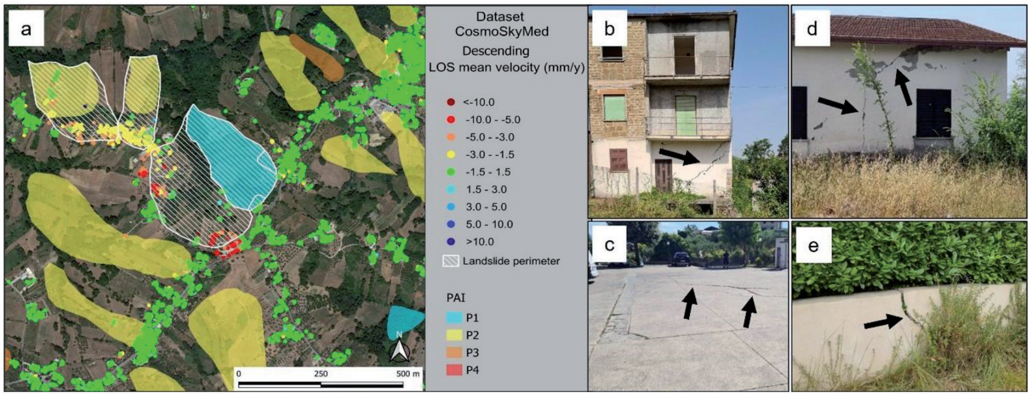

Fig. 7 - a) COSMO-SkyMed LOS velocity map (descending), with inventoried landslides from the PAI catalog, in the Strangolagalli municipality (Central Italy). The landslide perimeter defined by this work has been represented in white; b, c, d, e) photographs of the cracks on the most damaged buildings, roads, and walls

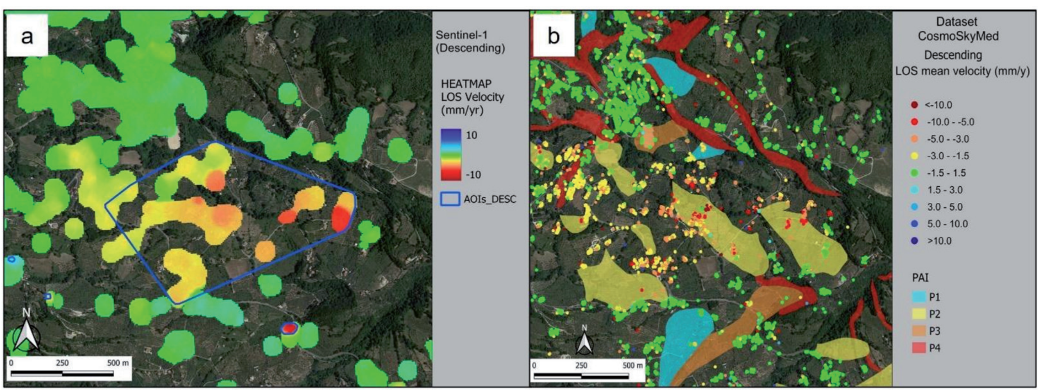

Fig. 8 - A-DInSAR results in the Arpino municipality (Central Italy); a) Sentinel-1 heatmap (descending) and AOI automatic identification; b) COSMO-SkyMed LOS velocity map (descending), with inventoried landslides from PAI catalog

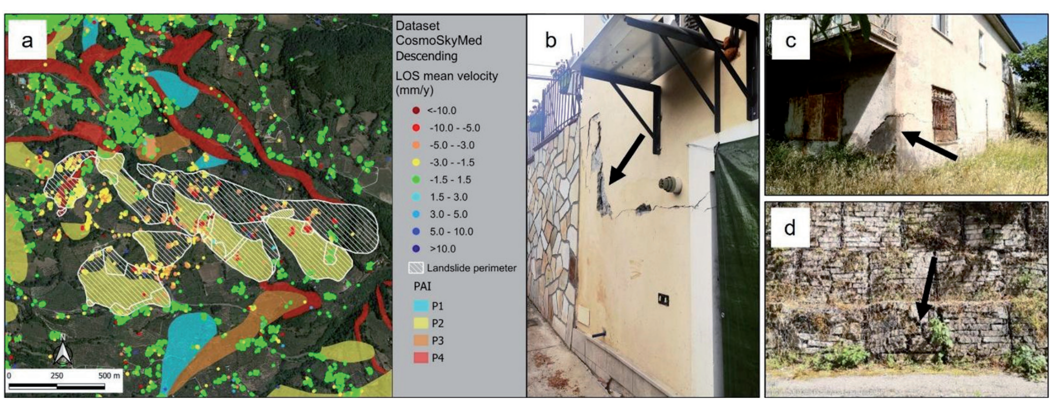

Fig. 9 - a) COSMO-SkyMed LOS velocity map (descending), with inventoried landslides from the PAI catalog, in the Arpino municipality. The landslide perimeters defined by this work have been represented in white; b, c, d

surfaces located within the first 10 m deep. The movement mechanism can be considered a translational sliding within the pelitic horizons of the Santopadre Formation, capable of supporting ephemeral aquifers in the conglomerate layers.

Locally, secondary phenomena identifiable as translational/rotational slips and flows affect the sectors affected by greater displacement rates and are characterized by impulsive movements with acceleration phases. Minor soil creeping processes due to the presence of deepening streams.

Integrating this information with the relatively high deformation rates from PS measurements and the field survey evidence, the different landslide processes mapped by the existing catalogs appear to be parts of a large process involving the entire slope (updated landslide perimeters in white in Fig. 9a). Therefore, the already mapped landslide polygons should be enlarged to include all the deforming areas, and the level of hazard should be increased, due to the current activity of the landslides (Fig. 9a).

DISCUSSION AND CONCLUSION

This work aimed to support the land management authorities in landslide risk mitigation by updating landslide inventories and verifying the state of activity of established processes, using (*i*) an automatic procedure exploiting A-DInSAR data that can identify several active slope deformations on a wide territory, and (*ii*) a detailed focus on slope scale with the support of on-site surveys and level of damage evaluation.

A-DInSAR is becoming an important tool to provide precise information and updates to be included in regional land management strategies and policies. The limits of this methodology are related to the typical drawbacks of the InSAR data characteristics and geometry of acquisition: (*i*) the achieved information concerns only extremely slow and very slow landslides, according to the Cruden & Varnes (1996) classification (*ii*) the movements in a north-south direction cannot be measured; (*iii)* poor information can be retrieved on vegetated areas. Despite the incomplete coverage of the studied area, the method allows the identification of hundreds of AOIs. The validation of the procedure has been carried out by verifying the ground truth in a subsample of selected AOIs which are confirmed to represent landslide processes.

Focused analyses, including also ancillary data, on-site surveys, and the exploitation of COSMO-SkyMed products, can lead to the characterization of the single landslide process. Buildings, roads, and infrastructures can act as movement indicators, and therefore, the exposed elements can represent a key factor. Many scientific papers are based on this idea (Cascini *et alii*, 2013; Di Maio *et alii,* 2018; Infante *et alii*, 2019; Peduto *et alii*, 2021; Cignetti *et alii*, 2023), contributing to outline the geometric and kinematic features of the landslides. The best practice would be to integrate A-DInSAR data, level of damage, and ground-based geotechnical monitoring data, such as inclinometric measurements or leveling, when available.

The comparison between the damage distribution and the A-DInSAR velocity maps shows that the buildings (especially with shallow foundations) located in the landslide-affected area exhibit higher damage severity in correspondence with the crown, the main and secondary scarps, where the highest velocity gradients are registered. The highest differential settlements may affect buildings located at the boundaries of the landslide, as discussed also by Nicodemo *et alii*, 2017, and Peduto *et alii*, 2021. In the examples shown in this paper, the degree of the building's damage generally corresponds to the velocity anomalies (as can be noted in Fig. 5 for the Belmonte Castello case study). However, in other cases, such correspondence could not be retrieved, as some factors could prevent the onset of damage such as the occurrence of rigid translation of the building that typically does not produce cracks. Moreover, renovation or maintenance works on the buildings, or a too recent onset of the deformation phase, prevent observing visible damage on the buildings.

To conclude, the results of this work highlighted that A-DInSAR big data managed semi-automatically at a large scale and then analyzed by integrating different data at a slope scale, represents a handy and effective tool to provide an update of the state of knowledge on active slope movements, supporting the local authorities in charge of mitigating landslide risk.

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REFERENCES

Amodio M. & Bovina G. (2002) - *Geologia del Lazio*. In: Sauli G., Cornelini P. *&* Preti F. (2002) - *Manuale di Ingegneria Naturalistica applicabile al settore idraulico*, Volume **2**: 37-42.

Angelucci A. (1966) – *La serie miocenica della media Valle Latina (Frosinone)*. Geologica Rom., **5**: 425-452.

Angelucci A., Bellotti P. & Valeri P. (1979) - *Analisi di facies dei sedimenti terrigeni tortoniani nella zona di Frosinone*. Geologica Rom., **18**: 127-132.

Antonielli B., Mazzanti P., Rocca,A., Bozzano F. & Dei Cas L. (2019) - *A-DInSAR performance for updating landslide inventory in mountain areas: An example from Lombardy region (Italy)*. Geosciences, **9**(9): 364.

Ao M., Zhang,L., Dong Y., Su L., Shi X., Balz T. & Liao M. (2020) - *Characterizing the evolution life cycle of the Sunkoshi landslide in Nepal with multi-source SAR data*. Scientific reports, **10**(1): 17988.

Barra A., Solari L., Béjar-Pizarro M., Monserrat O., Bianchini S., Herrera G. ... & Moretti S. (2017) - *A methodology to detect and update active deformation areas based on Sentinel-1 SAR images.* Remote sensing, **9**(10): 1002

Berardino P., Fornaro G., Lanari R. & Sansosti E. (2002) - *A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms*. IEEE Transactions on geoscience and remote sensing, **40**(11): 2375-2383.

Burland J. B., Broms B. B. & De Mello V. F. B. (1977) – *Behaviour of foundations and structures.* In: SOA Report, Proc of the 9th Int Conf on Soil Mechanics and Foundation Engineering, Volume **2**: 495-546.

Carrara C. & Giraudi C. (1995) - *La formazione Plio-Pleistocenica di Santopadre (Lazio, Italia Centrale).* Italian Journal of Quaternary Sciences, **8**(2): 535-552.

Cascini L., Peduto D., Pisciotta G., Arena L., Ferlisi S. & Fornaro G. (2013) - *The combination of DInSAR and facility damage data for the updating of slow-moving landslide inventory maps at medium scale.* Nat Hazards Earth Syst. Sci., **13**(6): 1527.

Centamore E., Dramis F., Di Manna P., Fumanti F., Milli S., Rossi D. ... & Nisio S. (2010) - *Note illustrative del Foglio 402 Ceccano.* Carta Geologica d'Italia, 1:50.000.

Cignetti M., Godone D., Notti D., Zucca F., Meisina C., Bordoni M. ... & Giordan D. (2023) - *Damage to anthropic elements estimation due to large slope instabilities through multi-temporal A-DInSAR analysis.* Natural Hazards, **115**(3): 2603-2632.

Cosentino D. & Pasquali V. (2012) - *Carta Geologica Informatizzata della Regione Lazio.* Università degli Studi Roma Tre - Dipartimento di Scienze Geologiche, Regione Lazio - Agenzia Regionale Parchi - Area Difesa del Suolo: Roma, Italy.

Cruden D. M. & Varnes D. J. (1996) - *Landslide types and processes*. In: Turner AK, Schuster RL (eds) *Landslides investigation and mitigation.* Transportation Research Board, US National Research Council, Washington DC, Special Report, **247**, Chapter **3:** 36–75.

Di Maio C., Fornaro G., Gioia D., Reale D., Schiattarella M. & Vassallo R. (2018) - *In situ and satellite long-term monitoring of the Latronico landslide, Italy: Displacement evolution, damage to buildings, and effectiveness of remedial works.* Eng. Geol., **245**: 218-235.

Fabbi S. (2018) - *Geology of the eastern slopes of the Simbruini Mts. Between Verrecchie and Capistrello (Central Apennines – Abruzzo, Italy).* Journal of Maps, **214**: 435-438.

Ferretti A., Prati C. & Rocca F. (2001) - *Permanent scatterers in SAR interferomery*. IEEE Transactions on Geoscience and Remote Sensing, **39**(1): 8-20.

Festa D., Bonano M., Casagli N., Confuorto P., De Luca C., Del Soldato M. ... & Casu F. (2022) - *Nation-wide mapping and classification of ground deformation phenomena through the spatial clustering of P-SBAS InSAR measurements: Italy case study.* ISPRS Journal of Photogrammetry and Remote Sensing, **189**: 1-22.

Infante D., Di Martire D., Calcaterra D., Miel P., Scotto Di Santolo A. & Ramondini M. (2019). *Integrated procedure for monitoring and assessment of linear infrastructures safety (I-Pro MONALISA) affected by slope instability*. Applied Sciences, **9**(24): 5535.

Mondini A. C., Guzzetti F., Chang K. T., Monserrat O., Martha T. R. & Manconi A. (2021) - *Landslide failures detection and mapping using Synthetic Aperture Radar: Past, present and future.* Earth-Science Reviews, **216**: 103574.

Nicodemo G, Peduto D, Ferlisi S, Maccabiani J (2017). *Investigating building settlements via very high-resolution SAR sensors*. In: Bakker, Frangopol, van Breugel (eds) Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure. Taylor & Francis Group, London: 2256-2263. ISBN 978-1-138-02847-0.

Nobile A., Dille A., Monsieurs E., Basimike J., Bibentyo T. M., D'oreye N.... & Dewitte,O. (2018) - *Multi-temporal DInSAR to characterise landslide ground deformations in a tropical urban environment: Focus on Bukavu (DR Congo).* Remote sensing, **10**(4): 626.

Piano Stralcio Per L'assetto Idrogeologico (P.A.I.) (2018) - *Autorità di bacino Distrettuale dell'Appennino Meridionale.*

Peduto D., Santoro M., Aceto L., Borrelli L. & Gullà G. (2021). *Full integration of geomorphological, geotechnical, A-DInSAR and damage data for detailed geometric-kinematic features of a slow-moving landslide in urban area*. Landslides, **18**: 807-825.

Solari L., Barra A., Herrera G., Bianchini S., Monserrat O., Béjar-Pizarro M.... & Moretti S. (2018) - *Fast detection of ground motions on vulnerable elements using Sentinel-1 InSAR data*. Geomatics, Natural Hazards and Risk, **9**(1): 152-174.

Trigila A., Iadanza C. & Guerrieri L. (2007) - *The IFFI project (Italian landslide inventory): Methodology and results*. Guidelines for mapping areas at risk of landslides in Europe, **23**: 15.

Trigila A., Iadanza C., Bussettini M. & Lastoria B. (2018) - *Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio*. Rapporto 2018. ISPRA, Rapporti 287/2018.

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