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SATELITE TECNIQUES FOR NATURAL HAZARD IN THE INTERNAL AREA OF BASILICATA REGION SOUTHERN ITALY – THE CASE HISTORY OF STIGLIANO TOWN

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EXTENDED ABSTRACT

Le aree interne della Regione Basilicata risultano particolarmente esposte ai fenomeni di dissesto idrogeologico in relazione alla dinamica intrinseca che ha condotto alla genesi e all'evoluzione morfostrutturale di questi territori. In tale contesto, le instabilità di versante rappresentano processi diffusi e spesso complessi, controllati da condizioni geologiche, geomorfologiche e idrogeologiche che favoriscono lo sviluppo di deformazioni lente e progressive, talvolta difficilmente riconoscibili attraverso sole osservazioni di campagna. L'impiego di tecniche di osservazione satellitare e di telerilevamento consente oggi di analizzare in modo oggettivo tali dinamiche, offrendo misure quantitative e spazialmente distribuite utili a supportare scelte più consapevoli ai fini della salvaguardia del territorio e della mitigazione del rischio.

La presente attività di ricerca si concentra sul centro abitato di Stigliano (provincia di Matera), assunto come caso studio pilota per l'analisi di deformazioni gravitativi lente in ambiente urbano. Il sito presenta caratteristiche territoriali e geologiche tipiche di numerosi centri appenninici, impostati su rilievi e versanti intensamente incisi da impluvi e valloni, dove l'evoluzione del reticolo idrografico e i processi di rimodellamento dei pendii esercitano un controllo diretto sulla stabilità. In tale quadro, alcune porzioni del tessuto urbano risultano inoltre costruite su corpi di grandi frane antiche, condizione che conferisce vulnerabilità intrinseca a settori localizzati e rende possibile la ripresa di movimenti preesistenti in presenza di fattori determinanti (infiltrazioni idriche, variazioni della pressione interstiziale, eventi pluviometrici intensi e, localmente, scuotimenti sismici).

I fenomeni di deformazione gravitativa che interessano l'abitato di Stigliano sono in parte noti in letteratura e riconoscibili sul terreno; tuttavia, non sono stati storicamente investigati in modo sistematico, soprattutto a causa della difficoltà di monitorare deformazioni a cinematica lenta prima della diffusione delle tecniche interferometriche satellitari. In questo lavoro l'analisi è stata condotta sfruttando i dataset interferometrici multi-temporali disponibili attraverso il portale EGMS (*European Ground Motion Service*), che mette a disposizione misure di spostamento derivate da Sentinel-1 con elevata continuità spaziale e temporale. L'obiettivo principale è stato quello di individuare e quantificare i movimenti lenti nell'area urbana e periurbana, con particolare attenzione ai settori potenzialmente più suscettibili e a quei segnali deformativi che, pur non producendo immediatamente effetti macroscopici, possono rappresentare precursori di evoluzioni più rapide e dannose, come accaduto tra gennaio e febbraio 2014 nella periferia meridionale dell'abitato.

Lo studio ha consentito di evidenziare e quantificare deformazioni significative nella porzione nord-orientale del centro abitato, caratterizzata da una dinamica in continua evoluzione. In particolare, l'analisi dei dati satellitari per la zona "a" mostra un trend deformativo con un cedimento medio di circa 4 mm/anno, associato a una componente di spostamento orizzontale verso Ovest dell'ordine di 2,4 mm/anno. L'intero settore nord-orientale evidenzia movimenti comparabili, con cedimenti generalmente compresi tra 3 e 3,5 mm/anno e una componente di spostamento planimetrico orientata verso Nord-Est. La distribuzione spaziale del segnale, la 34 sua coerenza e la persistenza nel tempo sono compatibili con una deformazione lenta di tipo composto, interpretabile secondo la meccanica dei fenomeni di spandimento laterale (*lateral spreading*), in un contesto nel quale unità più competenti possono risultare progressivamente deformate e disarticolate per scorrimento e cedimento su terreni argillitici più deformabili.

Nel complesso, i risultati ottenuti evidenziano come l'utilizzo integrato dei prodotti EGMS rappresenti uno strumento efficace per la diagnosi e la quantificazione di deformazioni lente in ambito urbano, fornendo indicazioni utili per l'individuazione dei settori a maggiore suscettibilità e per il supporto alle attività di pianificazione e gestione del rischio. L'approccio proposto costituisce inoltre una base operativa per successivi approfondimenti e integrazioni con rilievi geomorfologici di dettaglio, verifiche geotecniche e controlli idrogeologici, finalizzati alla definizione di scenari evolutivi e alla predisposizione di strategie di monitoraggio mirate alla salvaguardia del patrimonio urbano di Stigliano

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ABSTRACT

The inner areas of the Basilicata Region are particularly exposed to hydrogeological instability phenomena due to the intrinsic dynamics that led to the genesis of these territories. Satellite observation systems and remote sensing applications make it possible to objectively assess ongoing processes, also with the aim of supporting appropriate decision-making for land and environmental protection.

The research activity focused on a case study of a town in Basilicata: Stigliano, in the province of Matera, which can be considered a pilot site. In particular, the study aimed to analyze slow-moving ground deformations, which are not always immediately detectable but may represent precursory signs of more rapid and paroxysmal events, as occurred between January and February 2014 on the southern outskirts of the settlement.

The gravitational deformation phenomena affecting the town of Stigliano (MT) are partly known, but they have never been adequately investigated, mainly because they involve slow deformations whose monitoring was partly problematic before the development of techniques based on interferometric data. The study was carried out using interferometric datasets available through the EGMS portal (https://egms.land.copernicus.eu). The work conducted so far has made it possible to identify and quantify the significant deformations affecting the north-eastern sector of the town, characterized by continuously evolving dynamics. The analysis of satellite data shows, for area a), a trend with a settlement rate of about 4 mm/year, and a westward displacement of about 2.4 mm/year. In fact, the entire sector is characterized by comparable movements, showing a settlement of about 3–3.5 mm/year and a displacement towards the north-east. These movements are consistent with the mechanics of lateral spreading phenomena.

KEYWORDS: *slow-moving landslides, MT-InSAR, European Ground Motion Service (EGMS), lateral spreading*

INTRODUCTION

Landslides are widespread and potentially catastrophic phenomena across the Italian national territory, with particularly critical impacts near urban areas and major infrastructure. Within this framework, the inner areas of the Basilicata Region are especially exposed to hydrogeological instability, due to the complexity of the geological-structural and geomorphological setting and to the widespread occurrence of lithotypes with contrasting mechanical behaviour, often affected by stratigraphic and tectonic discontinuities and by hydrogeological conditions that favour the triggering and reactivation of slope instabilities. The recurrence of deep-seated gravitational slope deformations and slow-moving landslides, generally characterized by progressive evolution and by precursory signs that are not easily detectable through traditional observation approaches, therefore makes it essential to adopt monitoring tools capable of quantifying ongoing dynamics in an objective, repeatable, and spatially distributed manner.

From this perspective, the use of Remote Sensing Techniques (RST), such as satellite observations, laser scanning, and terrestrial interferometry, has become fundamental for the detection, monitoring, and forecasting of landslide phenomena. However, each of these methodologies presents specific limitations related both to the spatial extent of the affected areas and to the kinematics of the phenomenon under investigation (CASAGLI *et alii*, 2023). In this context, the integration of satellite remote sensing techniques, specifically Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR), has revolutionized the ability to monitor slow-moving slope deformations over the last few decades (CONFUORTO *et alii*, 2021; D'AMBROSIO *et alii*, 2023; NAPPO *et alii*, 2019; SIMEONE *et alii*, 2024). By exploiting data provided by the Sentinel-1 constellation and the European Ground Motion Service (EGMS), it is now possible to obtain displacement time series with millimetric accuracy over very large areas (COSTANTINI *et alii*, 2021). In the present study, these data were processed through a specific velocity vector decomposition algorithm, combining ascending and descending orbits in order to more accurately reconstruct the true components of ground motion in the Stigliano area. The aim is to correlate interferometric evidence with the ongoing local geomorphological evolution, providing a large-scale diagnostic tool for risk assessment, process understanding, and the safeguarding of the urban heritage.

The town of Stigliano (Matera Province) was selected as a pilot case study because it is affected by slow and persistent gravitational deformation phenomena, which are not always readily detectable through traditional approaches, yet may potentially evolve into paroxysmal conditions, as shown by recent events that affected peripheral sectors of the settlement. The integrated use of EGMS products therefore enables the detection and quantification of slow deformations and the identification of the most susceptible areas, providing a technical-scientific support for planning, monitoring, and mitigation actions.

STUDY AREA SETTING

Stigliano (Basilicata Region, Matera Province) is located along the inner margin of the Bradanic Foredeep, within the outer marginal belt of the Lucanian Apennines (Patacca & Scandone, 2007; http://www.isprambiente.gov.it/Media/carg/490_STIGLIANO/Foglio.html), in a morphologically dominant position on a ridge and on the immediately adjacent slopes, which are deeply dissected by gullies and small valleys. This setting, typical of many Apennine settlements built on terrigenous reliefs, results in a framework in which slope dynamics and the evolution of the drainage network exert a direct control both on hillside stability and on the configuration of the urban fabric, especially in the transition zones between the ridge and deeply incised valley sectors. Moreover, some parts of the settlement have been built on the deposits of large, ancient landslides, a condition that gives the site an intrinsic vulnerability, as it links the distribution of buildings to the pre-existence of masses already reshaped by gravitational processes and potentially subject to slow deformations and/or local reactivations under the action of triggering factors (Guerrichio & Melidoro, 1979, 1988b, Guerricchio, 2000, Sdao *et alii*, 2023).

GEOLOGICAL FRAMEWORK OF STIGLIANO URBAN AREA

The town of Stigliano is located in an inland area of Basilicata region on the eastern edge of the Apennine chain (Fig. 1). This area is characterized by a particularly complex and diverse geological structure linked to the tectonic uplift of the Lucanian Apennines, consisting of overlapping layers of various geological formations. The urban and peri-urban area is characterized by a pelitic–flyschoid bedrock, where lithotypes with strongly contrasting mechanical behaviour are associated within complex stratigraphic and tectonic relationships .A series of tectonic stacking structures have affected the outer edge of the Apennines, resulting in the geological formations often being disrupted and disturbed by tectonic deformations that have altered their original structure and stratigraphic relationships. In particular, outcrops of lithotypes attributable to the Numidian Flysch Formation [or Stigliano Formation (Auct.)] and lithotypes attributable to

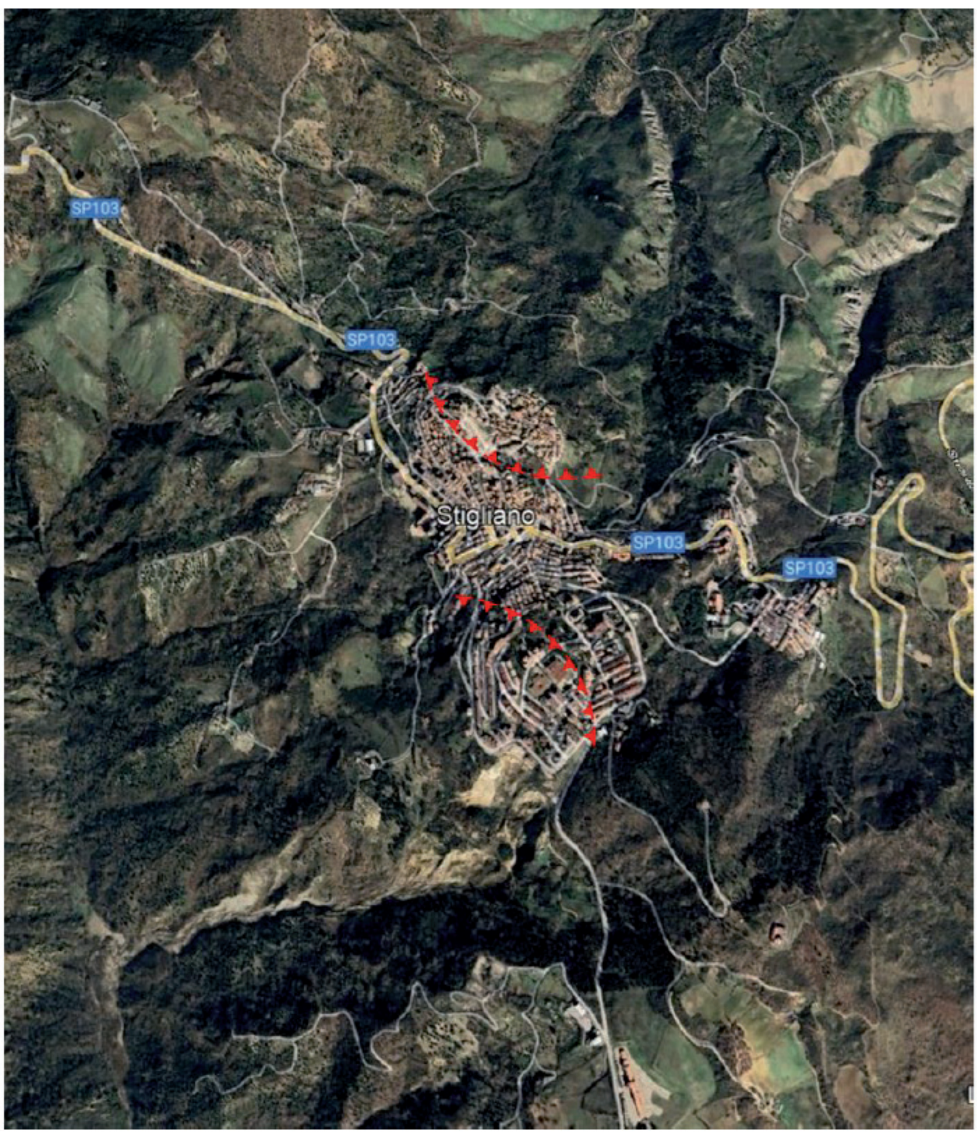

Fig. 1 - Satellite image acquired from Google Earth, with enhanced elevation scale, showing the town of Stigliano (Matera Province, 120 Italy) with the indication of the main DSGSD affecting the northern par and the southern part of the town

the Varicolored Clays (Auct.), as well as arenaceous marly and calcarenitic formations attributable to the internal Apennine flysch formations such as the Red Flysch, have been reported. On these Tertiary formations, near the town of Stigliano, lie weakly cemented polygenic conglomerates of predominantly continental origin with sandy layers, with a very irregular contact. Guerricchio & Melidoro (1988a) highlighted the complexity and irregularity of the stratigraphic successions present. As several other settlement of the inner Basilicata region Stigliano town is affected by gravitational processes and is subject to slow deformations under the action of triggering factors. From a geomorphological perspective, the entire town, including the Villa Marina district in the center of the town, is affected by large-scale, deep-seated gravitational slope deformation and numerous severe landslides, many of which are dormant, others active with slow dynamics or susceptible to partial remobilization with retrogressive evolution. These are mostly large, sometimes multiple, slides, influenced by the structural tectonic setting and tectonic contacts, the presence of clay intercalations, and contacts with the underlying Varicolor Clays.

The activity of these phenomena is evident throughout the centuries-old history of the town of Stigliano, and in this regard, a broad and detailed reconstruction of the landslides reported from historical sources. The Villa-Chiesa district in the centre of the town phenomenon is the oldest one, lies on a calcarenite slab undergoing further instability. This district, after 1907, had already been considered for relocation, which was never implemented. Other areas affected by severe instability include the La Bruto district and the urban sector of Via Fontana and Piazza Gramsci. In summary, the following units crop out (Fig.2):

- Varicolored Clays (Cretaceous-Eocene): hard clays and marly claystones, frequently occurring as small flakes and displaying various colours (wine-red, grey, greenish), often showing a chaotic fabric and locally incorporating more competent elements. These materials are regarded as highly prone to deformation and landsliding, consistent with a mineralogical composition dominated by expandable clay phases (with montmorillonite generally prevailing, and subordinate illite and kaolinite). This results in poor mechanical strength and "plastic" behavior in the more weathered and saturated levels. Marly units and arenaceous–pelitic alternations that contribute to the strong geomechanical heterogeneity of the slopes.
- Numidian Flysch (Stigliano Formation) (Early Miocene):

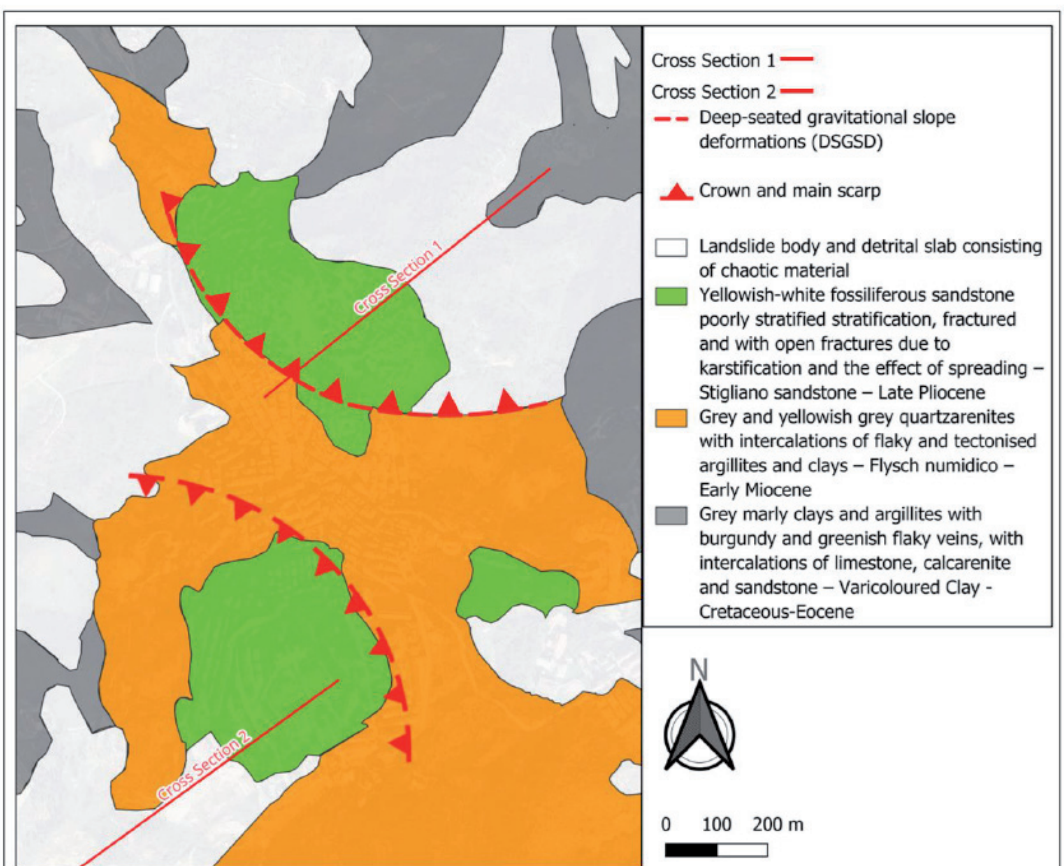

Fig. 2 - Geological map of the town of Stigliano with the evidence of the main scarp of the DSGSD (after Guerricchio & Melidoro, 144 1998 mod.)

a typical formation cropping out in the area, consisting of a more competent quartzarenitic member and a clayey–marly member. The quartzarenites, generally well cemented but locally friable, may display coarse grain sizes and predominantly siliceous cement, whereas the finer member is made up of quartzarenitic–clayey alternations and scaly marly claystones. The Stigliano Formation may occur in tectonic contact with the Varicolored Clays and with the Serra Cortina Marls, while in some sectors stratigraphic relationships with the Serra Palazzo Formation are preserved.

- Calcarenites (Stigliano Sandstone - Late Pliocene): in the Stigliano urban area, Pliocene cover deposits are often arranged in transgression over the older substratum and may be intensely fractured. Where calcarenitic slabs overlie mobile clayey terms or structural contacts, a complex deformational response is favored, potentially evolving into instability processes affecting the crest and marginal sectors.

The geotechnical response of the materials is largely controlled by the clay-rich lithotypes of the Varicolored Clays and by the finer members of the Numidian Flysch, which are characterized by a scaly/chaotic fabric and generally poor mechanical properties, showing a "plastic" or "semi-plastic" behaviour when saturated. Within this framework, the presence of groundwater (locally under pressure) and the action of water along discontinuities and contact surfaces represent key factors controlling slope stability conditions. Moreover, the juxtaposition of mechanically contrasting units, locally occurring through tectonic contacts, tends to generate repeated and articulated configurations such as imbricated slices and discontinuity surfaces that predispose to the development of large-scale landslides and deep-seated deformations, with kinematics that may partly resemble tectonic lineaments (Guerricchio & Melidoro, 1988a).

From a geomorphological viewpoint, the area is characterized by a complex slope dynamic, involving both deep-seated and superficial processes, with a tendency toward the reactivation of unstable volumes along the steepest and/or undercut sectors. In this setting, the presence of relict landslide bodies and of flow and accumulation deposits contributes to a "composite" slope arrangement, with alternating relatively stable sectors and sectors affected by slow deformation or prone to reactivation (Fig.3).

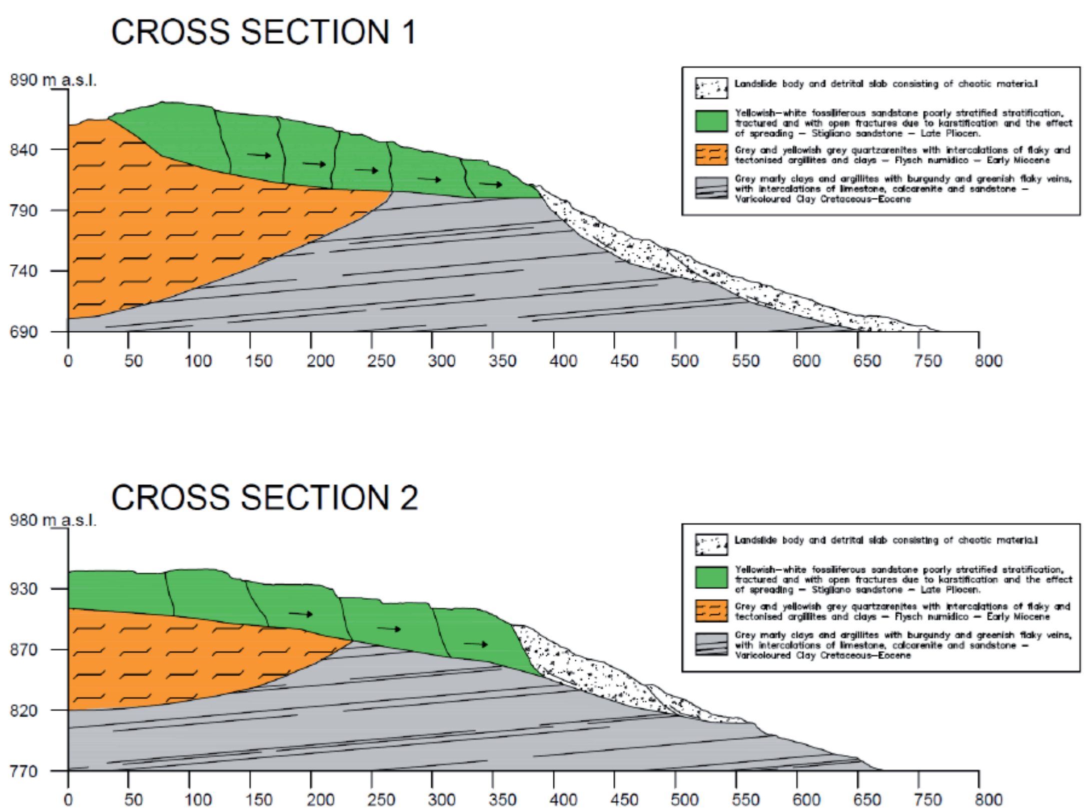

Fig. 3 - Topographic profiles (Cross Section 1 and Cross Section 2) corresponding to the section traces shown on the geological map of the town of Stigliano (Matera Province, Italy; fig.2). The profiles illustrate the elevation trend along the selected transects and provide the morphological reference framework for interpreting the geological–geomorphological setting and slope instability phenomena

In particular, the main types of landslide movements include:

- deep-seated gravitational slope deformations (DGSDs / DGPV);
- lateral spreading of rock masses over clayey materials;

both evolving in evolving in multiple sliding landslide and long earth flow.

At the urban scale, the sectors where the built-up area overlies calcarenitic slabs and/or pre-existing landslide bodies are especially significant: the Villa-Chiesa district, the oldest one, rests on a calcarenite slab undergoing further instability; other severely affected areas are located in the central part of the urban area. In these contexts, the observed instabilities may represent the reactivation of older movements, with the potential for acceleration or renewed activity under unfavorable hydrological conditions.

METHODOLOGY AND DISCUSSION OF RESULTS

Given the complexity of the deformation phenomena affecting the slope, but the low speed that characterizes the phenomenon, the quantification of displacements was performed using data from the European Ground Motion Service (EGMS), derived from the processing of SAR imagery acquired by the Sentinel-1 constellation. To overcome the intrinsic limitations of a single acquisition geometry - which provides velocity measurements exclusively along the satellite's Line-of-Sight (LOS) - a Python-based algorithm was developed and implemented to combine ascending and descending datasets (Fig. 4). The processing workflow initially involved the generation of a 50-meter regular sampling grid over the municipal territory, onto which the Measurement Points (MP) from both orbits were projected. By solving a system of linear equations that accounts for the incidence angles of the ascending and descending orbits, the code enabled the decomposition of the velocity vector into its components: the vertical component (V_V), indicative of subsidence or uplift, and the horizontal component (V_{EW}) along the East-West direction (Pepe & Calò, 2017). It is, however, essential to clarify that the results obtained do not represent the actual 3-D displacement components, but rather projections of the velocities onto the topographic plane, specifically the East-Up (EU) plane (Brouwer & Hanssen, 2023). To transform the LOS velocities into the components of motion, a linear equation system combining ascending and descending acquisitions was implemented (Equation 1).

$$\begin{cases} V_{asc} = V_V cos\theta_{asc} + V_{EW} \sin\theta_{asc} \\ V_{desc} = V_V \cos\theta_{desc} + V_{EW} \sin\theta_{desc} \end{cases} \qquad (1)$$

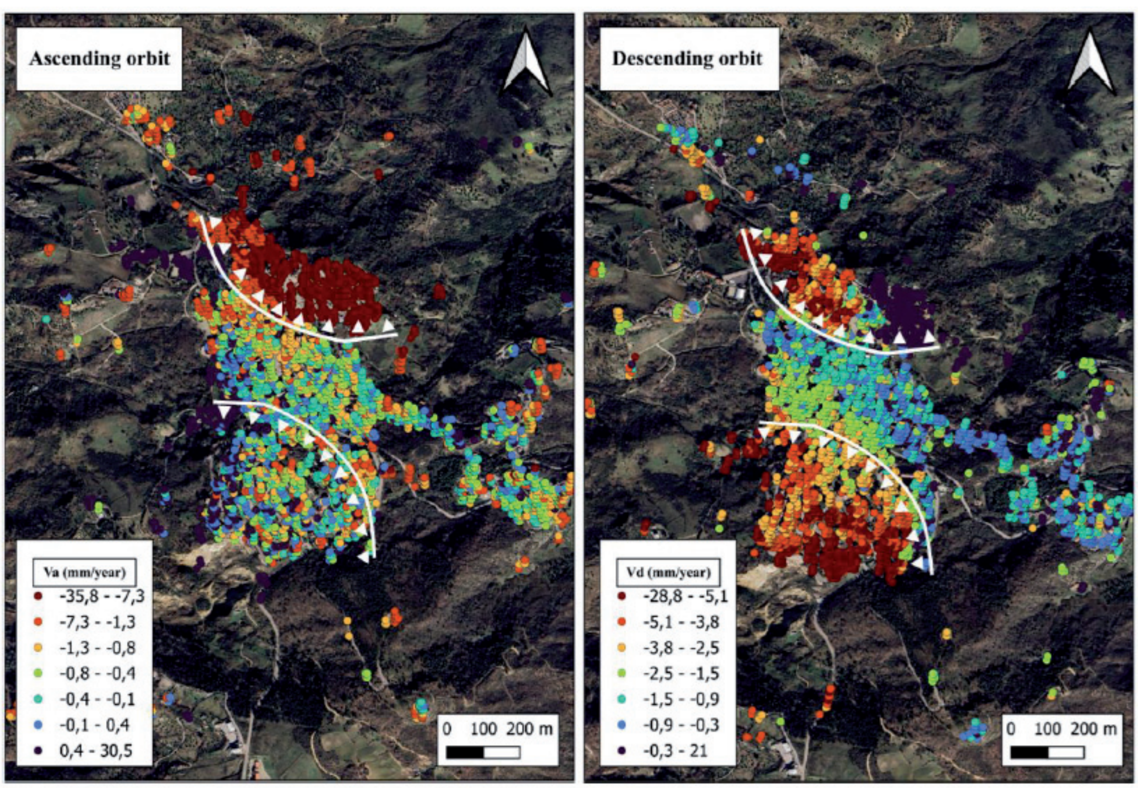

Fig. 4 - Spatial distribution and average annual velocity of the Measurement Points (MP) obtained from the EGMS service for the Stigliano area. On the left, data relative to the ascending orbit are shown (V_{asc}), while on the right, those of the descending orbit are presented (V_{desc}). The color scale indicates the displacement velocity along the satellite Line-of-Sight (LOS), expressed in mm/year. There is evidence of the main scarp of the studied DSGSD

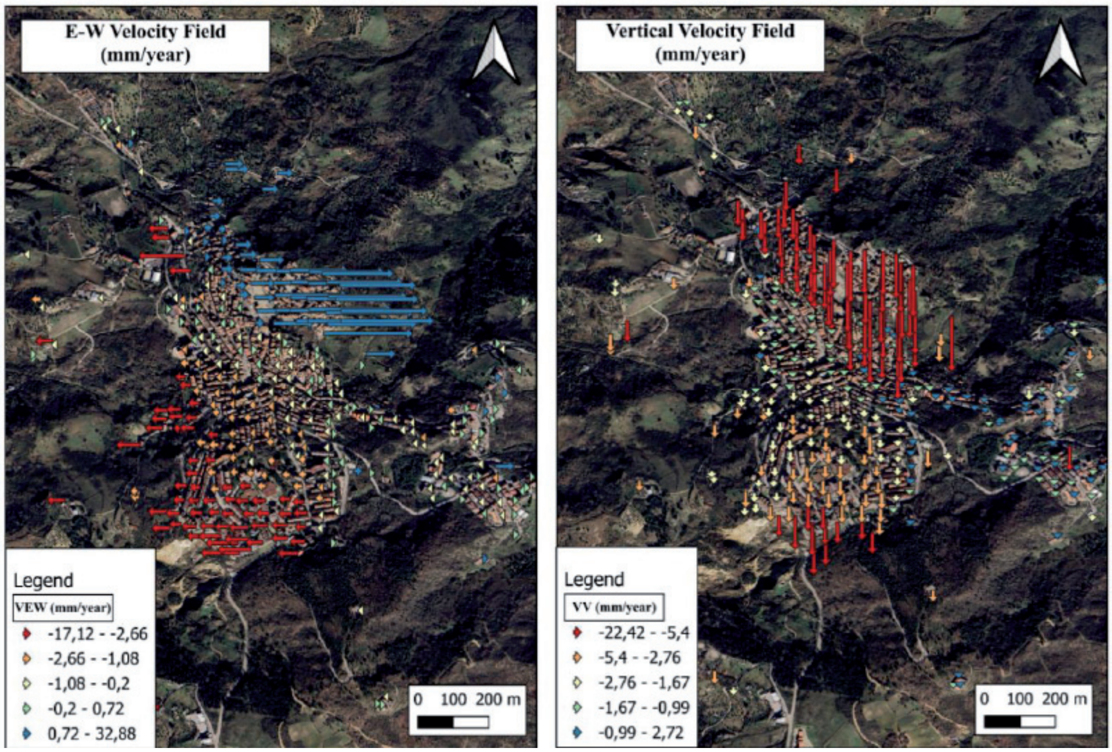

Fig. 5 - Average annual velocity maps obtained from the decomposition of EGMS data for the Stigliano case study. On the left, the East-West horizontal velocity field (VEW) shows the lateral displacement vectors of the slope, consistent with the local morphological evolution. On the right, the vertical velocity field (VV) is represented, where warm tones highlight areas subject to greater subsidence

The system is based on the acquisition geometry defined by the incidence angles. In this system, and V_{asc} and V_{desc} represent the velocities measured along the LOS for the ascending and descending orbits, respectively. The terms θ_{asc} and θ_{desc} denote the radar beam incidence angles relative to the vertical, for the ascending and descending orbits, respectively. The resulting quantitative analysis (Figg. 4 and 5) allows for the correlation of displacement vectors with damage evidence detected within the urban fabric, providing an objective basis for interpreting the soil-structure interaction typical of slow-moving gravitational processes. However, this methodology does not allow for the retrieval of the North-South velocity component, thus preventing the reconstruction of the full 3D displacement vector. The results demonstrate that within the built-up area, specifically in the north-western sector, downward and westward 191 movements are present, which are consistent with the landslide crown identified in the literature (Figure 2). These interferometric findings confirm the presence of a slow-moving gravitational deformation affecting the urban fabric, similar to observations of Deep-Seated Gravitational Slope Deformations (DSGSD) in other historical centers of the Southern Apennines. Conversely, in the southern part of the town, the data highlight gravitational 'draw-down' phenomena in the area affected by the catastrophic landslide of the center for senior people in 2014 in Stigliano, that evolve in a long earthflow. The persistence of these velocity vectors indicates an ongoing kinematic process, emphasizing that these flows cannot be considered quiescent, but rather active dynamics that continue to exert stress on existing infrastructure. The spatial distribution of these velocities, measured with millimetric precision through the decomposition of EGMS data, allows for the mapping of the phenomenon's areal extent and the correct interpretation of the damage observed on buildings and the road network, which reflects the accumulation of long-term cumulative deformations.

CONCLUSION

The results demonstrate that within the inhabited area, specifically in the north-western sector, downward and westward movements are present. These findings are fully consistent with the landslide crown historically identified in the studies by Guerricchio & Melidoro (1988), confirming the persistence of a deep-seated deformation dynamic. Although characterized by millimetric velocities, these displacements generate, over the long term, internal stress (co-action) within the structures that can compromise their functionality and structural integrity. Such an approach, in addition to ensuring cost-effective monitoring over broad areas, is crucial for preventing the irreversible deterioration of the built heritage and ensuring public safety in geologically complex environments.

Authors' personal contributions

This work was developed in its various aspects with equal contribution from Lorenzo Di Taranto and Antonio Fiorentino, under the scientific coordination of Prof. Angelo Doglioni and the supervision of Prof. Vincenzo Simeone.

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