Integrated Use of Geomatic Methodologies for Monitoring an Instability Phenomenon

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Abstract. The growing exposure of the Italian territory to hydrogeological risk, also worsened by the influence of climate change, has made the occurrence of catastrophic phenomena, such as landslides and floods, always more impactful. In this frame, geomatic methodologies can provide a crucial support in properly characterizing a potentially critical instability phenomenon, both from the spatial and kinematic view. In this work, the integrate use of geomatic methodologies, i.e., Multi-temporal Interferometric Synthetic Aperture Radar (MTInSAR) technology and structural sensors, namely biaxial tiltmeters, were employed to kinematically investigate the behavior of an urban area affected by a landslide, located in the Apulian territory. The MTInSAR analysis carried out on Sentinel-1 SAR acquisitions showed a strong non-linear behavior in the displacement-time trends, also highlighting the presence of differential motions constituting a threat for buildings. As regards the main retaining structure, currently damaged by the landslide, automatic measurements provided by the tiltmeters confirmed the presence of more active areas, as detected by the SAR observations.

The outcomes of this work provided key information to the structures responsible for the management of the risk connected with the instability and allowed to address the proper design of the mitigation works.

Keywords: landslide geomatic monitoring · MTInSAR · tiltmeters · non-linear displacements · Sentinel-1

1 Introduction

Hydrogeological instability, triggered by natural and/or anthropogenic factors, is one of the most debated issues at global scale, which currently involves the scientific community [1]. The Italian peninsula, because of its geological structure and the growing anthropic pressure, is particularly subject to instability phenomena [2].

The study [3] developed by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale - Italian Institute for Environmental Protection and Research) estimates that 93.9% of Italian towns are subject to instability phenomena, such as landslides, floods

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[4] and/ or coastal erosion [4]. The impact of landslides in Italy is incredibly significant, thus representing a real social and economic problem [5, 6].

In recent years, several catastrophic events affected the Italian territory, the last of which was recorded on the Ischia Island in November 2022, causing the death of 12 people and damage to the economy and tourism [7].

The availability of reliable techniques aimed at monitoring instabilities becomes then increasingly crucial to counter these events and helps to adopt effective solutions for mitigating their effects [8–10].

The risk mitigation strategies, that can help to avoid a disastrous development of an instability or support the emergency management phase of the event, encompass a deep knowledge of the phenomenon, to better understand its evolution and accurately monitor its effects [11, 12].

In this frame, the geomatic monitoring based on ground and aerial/satellite techniques and sensors, provides the ability to properly characterize the field of displacements and help the safeguard of the infrastructures and people involved [13]. The methodologies to be employed must be appropriately identified according to the magnitude of the phenomenon, the extent and accessibility of the study area.

The implementation of population warning methodologies to safeguard human lives must be carried out through Early Warning Systems, unless a routinary monitoring activity cannot be conducted or when cost-benefit analysis is unfavorable [14, 15].

In the last decades, the technological evolution has facilitated the use of more advanced sensors and has made available large databases consisting of multiple territorial information, as in the case of the European Copernicus program [16].

The Copernicus program, with its completely ‘free & open’ data policy, provides a huge repository of historical SAR data and allows a tight monitoring of large areas, also allowing to perform back-analyses preparatory to the design and the installation of ground-based monitoring systems. The Copernicus program allows to benefit from an additional service, known as the European Ground Motion Service (EGMS), which provides a consistent and high-quality information on natural and anthropogenic ground motion, with millimeter accuracy [17].

This work focuses on the analysis of SAR data acquired by the Sentinel-1 mission within the Copernicus program, relating to a town, situated on the Dauno Sub-Apennine in the Apulia region, damaged by a gravitational landslide phenomenon. The satellite data allowed a detailed kinematic characterization of the displacement field affecting the urban area, which is partially located on the rear scarp of the instability.

The deformation pattern was examined referring to a seven years-spanning data set, using the Multi- Temporal InSAR (MTInSAR) methodology. The study of displacement trends shown by individual scatterers was coupled with an areal analysis, aimed at highlighting differential behaviors and the possible presence of different temporal phases in the activation of the instability phenomenon.

The analysis played a key role in drawing up the design of the geomatic monitoring system currently running on the site, which included the implementation of a tiltmetric network, which measurement are also examined.

2 The Study Area

The investigated area is located in the Apulian territory, on the border with Molise region. The presence of a gravitative landslide required the intervention of the competent authorities to understand the phenomenon and plan the proper interventions. However, the instability has been observed since the late 1800 and its development could be attributed to several causes which include seismic events. In order to remediate the instability effects, a series of retaining works have been undertaken since 1950. The most recent retaining wall has been built in 2006. Moreover, the presence of differential collapses in some buildings has determined their demolition.

A comparison between the aerial images acquired in 2002 (Fig. 1A) and in 2022 (Fig. 1B) evidences the evolution of the built area.

The landslide phenomenon threatens the settlement area and also involves a zone called the Crojo spring, located north-west of the historical center.



Fig. 1. Study area plan for 2002 (A) and 2022 (B). The areas highlighted in the white square belong to the Crojo spring. The red line delineates the rear scarp of the landslide area. Source: Google Earth Pro. (Color figure online)

3 Methodologies Employed

In the present work, multi-temporal satellite interferometry MTInSAR technique and structural monitoring sensors, operated through the installation of tiltmeters along the retaining wall, are being employed. The tiltmeters implement an alert system based on the exceeding of a predetermined inclination threshold, which can provide an early warning in case of sudden variations of the tilt angle of the wall [18].

3.1 MTInSAR

Among geomatic technologies, satellite interferometer techniques play a leading role, due to its accuracy and its cost-benefit ratio. MTInSAR allows to survey ground displacements on the earth surface, providing information on a certain portion of territory with a fixed revisit time. The SAR technique, Synthetic Aperture Radar, has the potential to observe and measure deformations of the earth's surface over large areas with a high degree of detail.

The Sentinel-1 (S1) constellation, framed in the Copernicus mission, featured two satellites (S1A-B) operating in C-band and following a near-polar orbit, characterized by a revisit time of approximately 6 days until 2021. Nowadays, after the decommissioning of the S1B satellite, the revisit time has been significantly reduced to 12 days. However, the free availability of archive images, acquired from 2015 to present, and a relatively high spatial resolution (20x5m) over extensive areas, allow to obtain an accuracy of up to 1 mm in terms of displacement trend [19].

SAR interferometry (InSAR) relies on the basic principle of evaluating the potential dissimilarities between two images captured with a radar sensor under identical geometric conditions, but during two different instants of time [20].

The analysis performed by the Persistent Scatterers Interferometry (PSI) technique needs the identification of radar marks, called Permanent Scatterers (PS), both natural and anthropic (e.g., rocks or man-made structures), distinguishable in the entire image stack processed, so that they can be compared over time. The PS must not change their 'electro-magnetic signature' and phase information, to be clearly identifiable even if atmospheric or climatic conditions change. The quality of the interferometric fringes depends on the correlation between the two SAR images.

Correlation can be estimated in terms of interferometric coherence γ [21], ranging between 0 and 1, where $\gamma \approx 0$ indicates a strong measurement noise. This is generally noticeable in heavily vegetated areas or large bodies of water. By several observations during time and in the identical area, continuous monitoring of ground displacements is attained.

Therefore, MT-InSAR technique can detect ground displacements associated with pixels on the corresponding image. The main outcome of the technique is the identification of measurement points spatially georeferenced (by longitude, latitude and ellipsoidal height) and characterized by i) a coherence value defining the stability of the target and its reliability ii) the annual average value of the velocity computed along the Line of Sight (LoS), which is the direction joining the sensor and the target,perpendicular to the orbit and inclined by an angle θ - called off-nadir, iii) and the displacement time series during the monitoring period [22].

3.2 Tiltmeters

Remote biaxial tiltmeters allow the monitoring of inclination fluctuations of a structure over time along two axes [23].

Generally, the measurements acquired by this category of sensors are strongly influenced by the temperature parameter and its variation. Direct or indirect solar radiation transfer, by warming the structure where the sensor is installed, and the sensor itself, triggers a disturbing impact on the tiltmeter. To consider the impact of this parameter, the device is generally equipped with thermistors recording the temperature value.

The instrument provides punctual values, i.e., indicative of the inclination variations of a limited portion of the monitored object, Hence, to accurately describe the behavior of a complex construction, the use of several sensors is required. However, the opportunity to record long-term time series (in the order of years) at regular intervals can greatly improve the knowledge of the geometry and deformational speed of structures affected by the instability, thus providing information on the evolution of the study area [24].

4 Data Analysis

4.1 MT-InSAR Data

Considering the favorable orientation of the built area and the retaining wall (north-south) nearly perpendicular to the LoS, and the steepest path direction (west-northwest) of the slope underneath the instability zone, the study area was analyzed through the data obtained along the descending orbit from March 2015 to April 2021, with an average frequency of 6 days.

The interferometric dataset has been acquired within the European Copernicus Program from the S1 satellite constellation and processed using the approach shown in [25], and provided in the frame of a collaboration between the Polytechnic University of Bari and the Government Commissioner for the environmental risk of the Apulia region, which oversees the implementation of proper risk mitigation strategies. A simple filtering process has been applied to the historical time series; given the raw data, a moving average has been computed on five acquisitions and a 1 σ test has been assessed on the central value of the considered measures to remove possible outliers. If not accepted by the test, the measured value has been classified as an outlier and consequently replaced with the value from the moving average.

The displacement average velocity map computed along the LoS in Fig. 2, evidence the PS belonging to the settlement area most affected by the instability, which is the active retrogressive scarp at the head of the landslide. The scatterers pertaining to the Crojo spring are also displayed.

The recorded speeds are shown in the Fig. 3A. Nonetheless, in pursuit of more trustworthy information about the displacement and velocity fields, the PS characterized by a coherence ≤ 0.6, (Fig. 3B) were discarded.

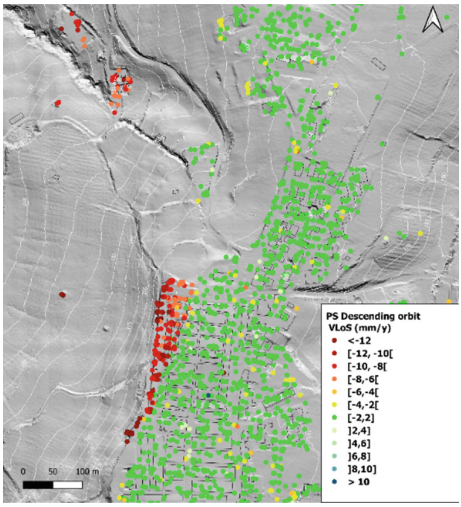


Fig. 2. Average velocity map along the Los between March 2015 and April 2021, computed on the data acquired on the descending track.

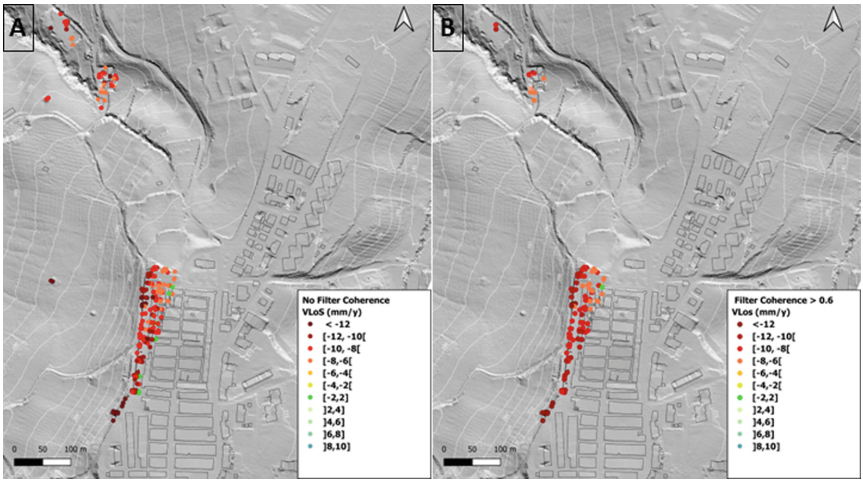


Fig. 3. Velocity map without coherence filter (A) and filtered by coherence > 0.6 (B)

As the Table 1 clearly indicates, the distribution of PSs with a velocity value of less than −4 mm/year remains almost unchanged in percentage terms [26].

Table 1. Number of PS distributed in the different ranges.

Velocity ranges (mm/ years)	Number of PSs		Per cent of PSs	
	No Filter C	C >0,6	No Filter C	C >0,6
≤-12	22	12	11,06	9,92
]-12;-10]	42	30	21,11	24,79
]-10;-8]	78	50	39,2	41,32
]-8;-6]	45	27	23,12	22,31
]-6;-4]	1	1	0,5	0,83
]-4;-2]	0	0	0	0
]-2;2]	10	1	5,03	0,83
]2;4]	0	0	0	0
]4;6]	0	0	0	0
]6;8]	0	0	0	0
]8;10]	0	0	0	0

Following these results, the analyses have been conducted on the sub-dataset characterized by a coherence value > 0.6.

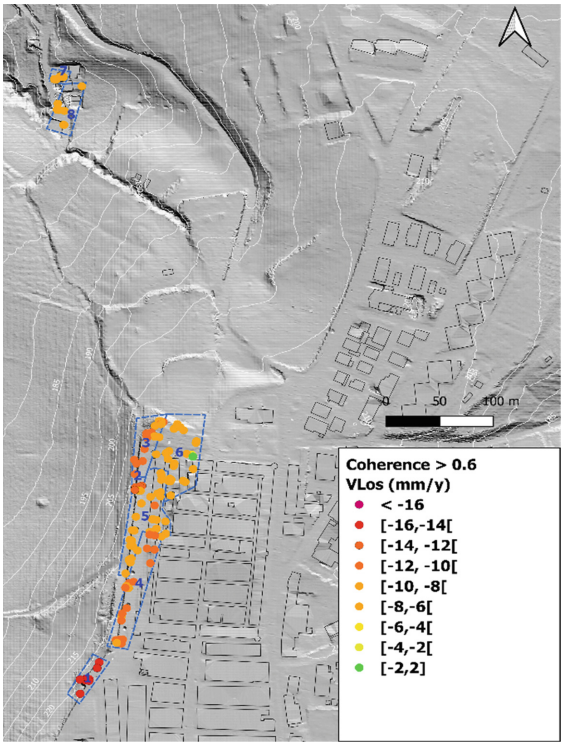


Fig. 4. Cluster characterized by a comparable average velocity along the LoS.

The evaluation of the ground motion map brought out several clusters characterized by a comparable behavior, in terms of average velocity (Fig. 4).

Table 2. Average velocity of the identified clusters

N.cluster	Average Vel (mm/y)	Std. Dev. Vel
1	-14,29	0,35
2	-13,04	0,42
3	-10,25	0,79
4	-10,22	0,37
5	-9,08	0,60
6	-7,42	0,74
7	-8,38	0,14

As described in [27] the PS trend throughout the entire observation time, validated using COSMO-SkyMed acquisitions and levelling measurements, is marked by a strongly non-linear behavior, (Fig. 5), where periods showing almost constant and relatively low velocities are interspersed with short acceleration stages of the landslide, characterized by a higher velocity. The graphs refer to nine PS belonging to the retaining structure (A-I) and one target located in the Crojo area (L).

In addition, the time series related to two points approximately adjacent to the points A and F examined in Fig. 5, available from EGMS portal, have been analysed into the present study, and the relative trend have been compared, as evidenced in Figs. 6 and 7. The points viewed through the EGMS portal considered were selected considering their coherence value, i.e., greater than 0.6, and undergone the simple filtering process as described above. The peculiar behaviour remains substantially confirmed when comparing the two datasets for both examined points.

A more refined investigation has been conducted by deepening the fourth dimension of the phenomenon, namely its spatial evolution over time, also with the purpose of evidencing possible remobilizations of the same portions of the unstable area in different periods. Starting from the peculiar displacement pattern, detected in the upper part of the instability including the north-west sector of the urban area and the Crojo spring, the whole dataset has been split in into three-month temporal intervals.

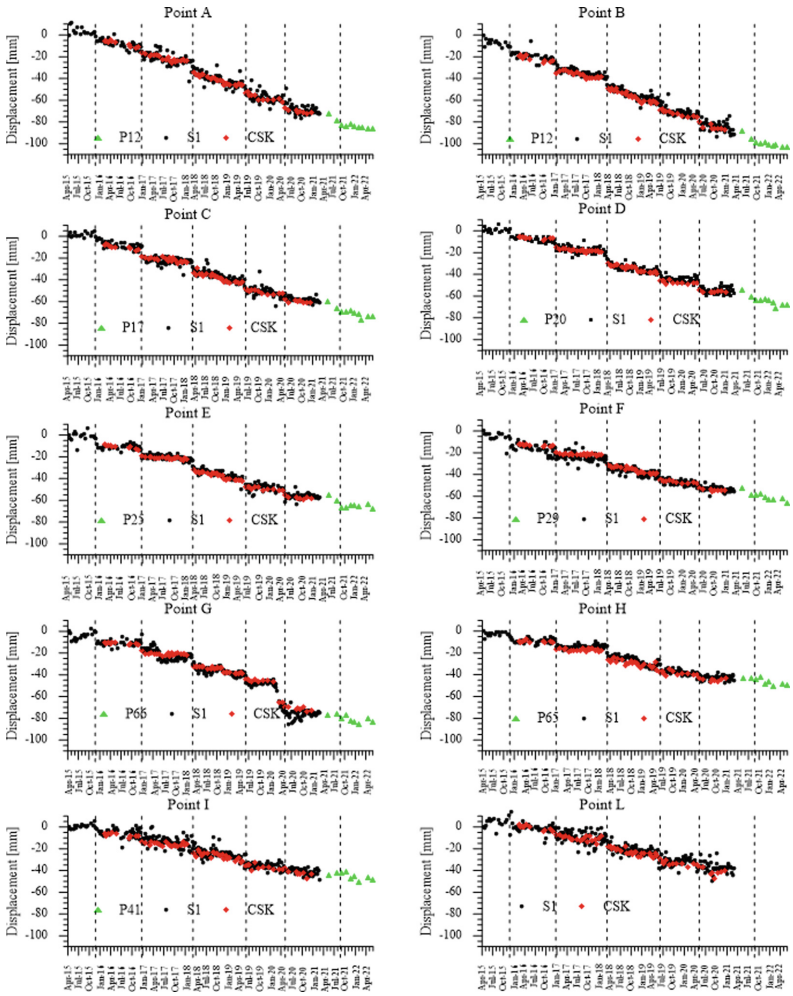


Fig. 5. PS trend evidenced by Sentinel-1 data (S1 series) and validated through COSMO-SkyMed (CSK series) data and levelling measurements (Pi series) (image source: [27]).

26 sub-datasets were then derived, processed and classified to highlight the presence of PS with a comparable behavior.

The back analysis highlighted that the whole unstable area is simultaneously involved in the acceleration phase, during which the average velocity has a sudden increase (Fig. 8a, d). The southernmost corner of the retaining structure, within the cluster 1, shows relevant velocities during the periods after the acceleration phase (Fig. 8b, c, e, f). In Fig. 8(b and c), also the northern part of the retaining structure shows significant displacement rates during the periods (Fig. 8c and e), while the section south of the latter highlight motions (Fig. 8b and f). During the stages characterized by the maximum displacement rate, approximately 50% of the sample belongs to the cluster typified by

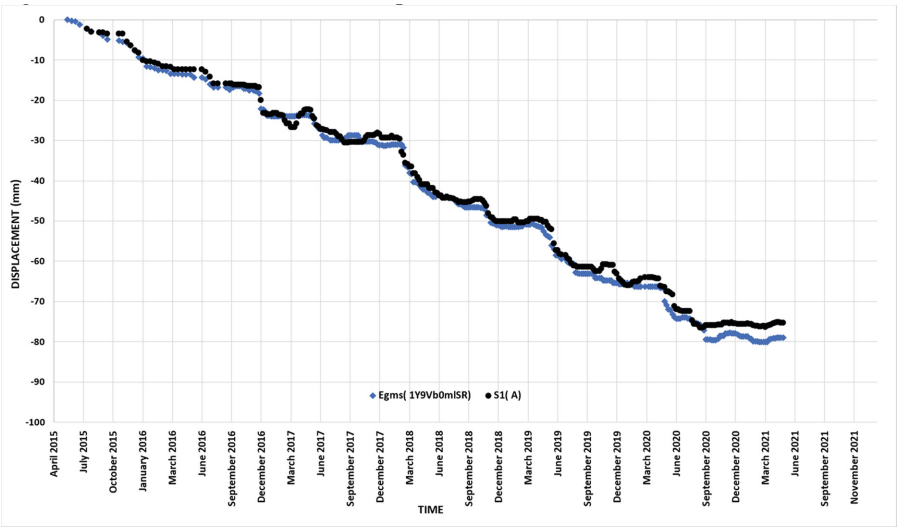


Fig. 6. PS trend evidenced by Sentinel-1 data (S1 A) compared with Egms point.

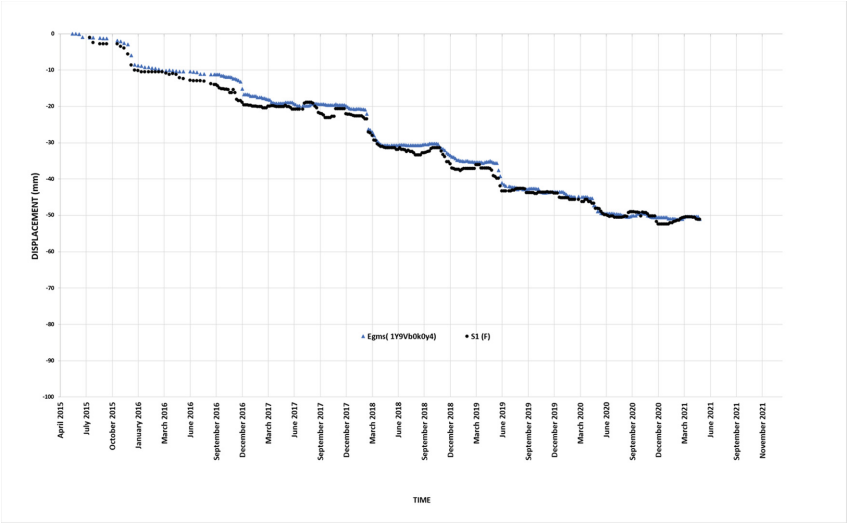


Fig. 7. PS trend evidenced by Sentinel-1 data (S1 F) compared with Egms point.

a velocity ranging from −20 to −40 mm/year, while the remainder is distributed in the two immediately contiguous classes.

The impact of the ground motion on a building is generally limited when the displacement affects the entire structure at the same time, leading to a rigid and homogeneous translation. On the contrary, a differential displacement at the foundations level, in relation to the soil-structure interaction, could trigger a gradient in the stress-strain condition

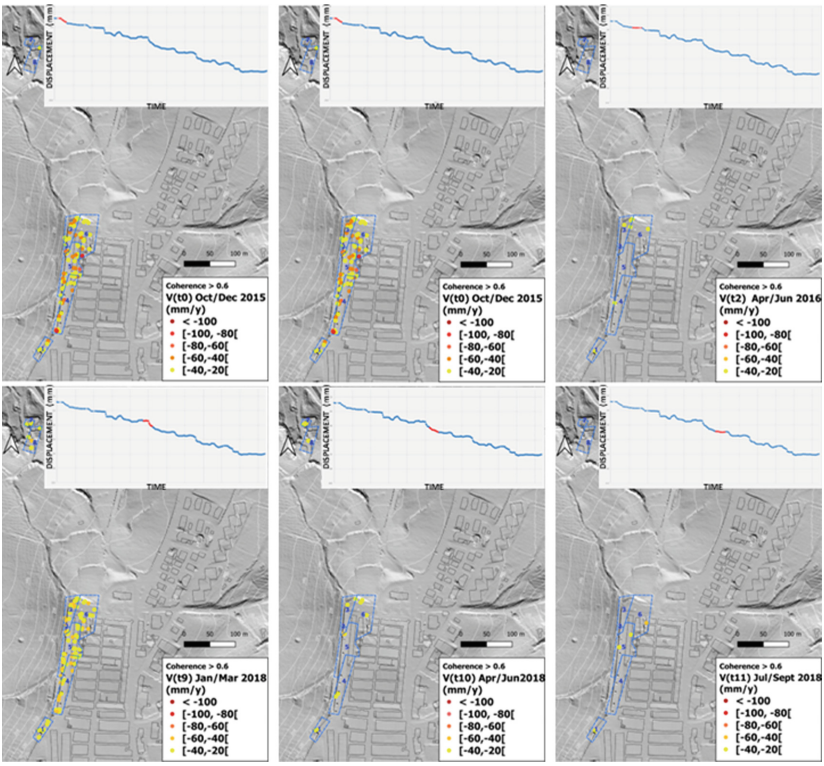


Fig. 8. 6 of 26 Sequences for planimetric velocity map

of the edifice, resulting in severe damages and, in worst cases, in the failure of the building. The effects of the differential movements can be spotted on the townhouses located across the border between the stable and unstable area, which are subject to a significant displacement component on the side of the landslide edge. The impacts of this dynamic are shown in Fig. 9. Based on these results and the damages detected on the field, the competent authorities have ordered the evacuation of the buildings within the subsiding area.

4.2 Tiltmeter Data

Following the outcomes of the MTInSAR back analysis, in September 2021, eight biaxial tiltmeters (CE01 to CE08, Fig. 10) have been installed on the containing structure to provide high-frequency monitoring of the wall and a prompt alert in case of a sudden change in its inclination, indicative of an acceleration of the instability process. The tiltmeters are remotely controlled and record the temperature on the first channel, namely Ch1, and the tilt values along two additional channels, Ch2 and Ch3, in transverse and longitudinal direction to the structure respectively, at hourly intervals. The observed data were processed using a moving average over a range of 24 h to minimize the effects of the daily temperature fluctuations. Except for the CE08 sensor, located in the southernmost



Fig. 9. Evidence of instability

part of the structure, on the long-term period the small inclination variations recorded by the system show essentially a direct or inverse correlation on the temperature (Fig. 11), indicating the absence of planimetric displacements until January 2023. This dependence is probably related with the microclimatic conditions and mechanical features of each tiltmeter.

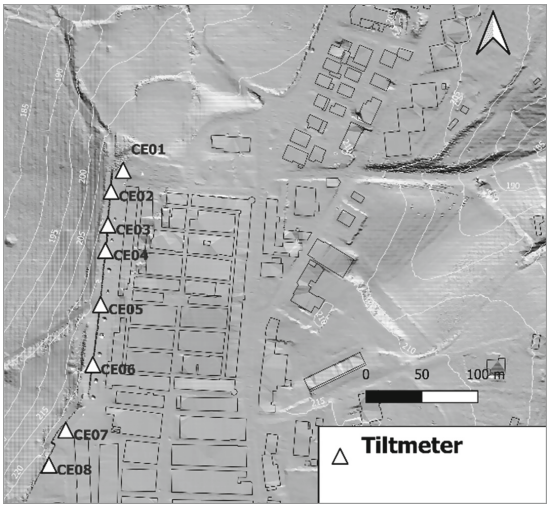


Fig. 10. Tiltmeters location.

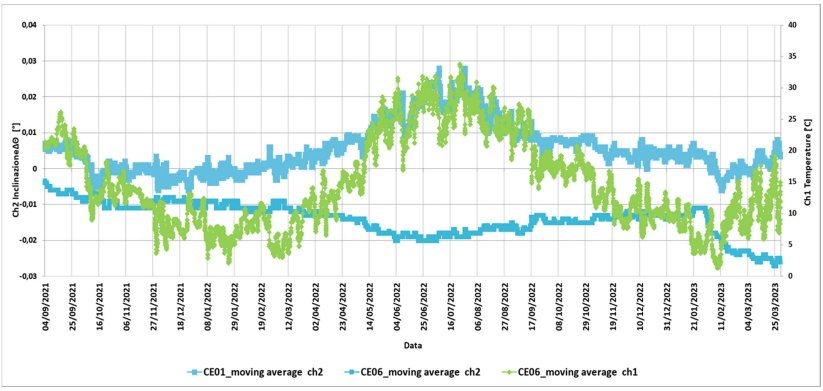


Fig. 11. Direct or inverse variation of the inclination Ch2 with temperature (Ch1)

As regards the time interval between the installation of the system and January 2023, the CE08 sensor recorded a rotation that caused an estimated shift at the head of the wall of approximately 2cm, considering the pivot coinciding with the base of the structure. However, between the end of January 2023 and the end of February 2023, fast changes in inclination with respect to the Ch2 channel (i.e., perpendicularly to the wall) were recorded also by CE03, CE04, CE07 tiltmeters. Whereas at the time of writing this paper, the small changes seem to be temperature-related again. Figures 12 and 13 show the trends of the entire series.

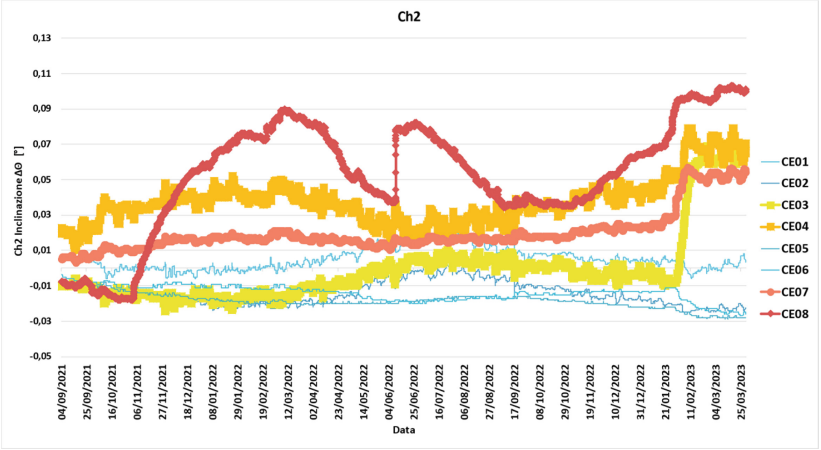


Fig. 12. Variation in tilt in direction perpendicular (Ch2) to retaining structure measured by all tiltmeters.

The tilt variation first involved CE07 and CE08, located on the south side of the retaining structure, followed by a sudden variation of inclination recorded by CE03 and CE04. This increased activity could be related the mobilization of two areas more active

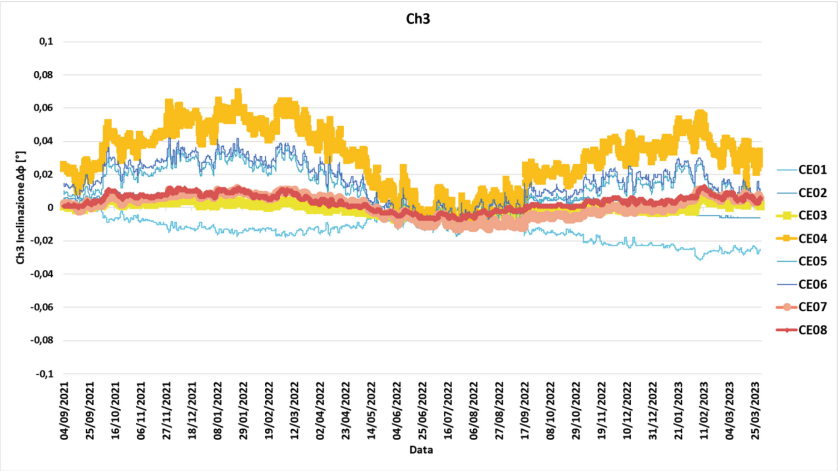


Fig. 13. Variation in tilt along the direction (Ch3) to retaining structure measured by all tiltmeters.

than the surrounding zones, as evidenced by the MTInSAR analysis. The duration of this intensity variation seems to confirm the evidence of MTInSAR analysis, where the succession of phases is typified by periods with small displacements and phases in which the magnitudes are considerably larger.

5 Conclusions

The aim of the presented work was to investigate and kinematically describe the phenomenon that affects the study area. To this purpose, several geomatic methodologies which led estimate the displacement field, were jointly applied. The results provided by the MTInSAR analysis, through processed data from the Sentinel-1 database, gave evidence of the extension of the urban area affected by the landslide, showing increasing velocities moving from the edge of the stable area towards the retaining wall.

The SAR data analysis also brought out the presence of clusters characterized by different mean displacement velocities, computed along the LoS, which can trigger differential displacements resulting in severe damages to structures. The investigation of the phenomenon from a time perspective, reveals a peculiar behaviour of the instability area, evidencing displacements along the LoS evolving by following a non-linear trend.

High-precision geometric leveling validated and reinforced the results obtained from satellite observations, confirming the detected trend. Moreover, the focus on the temporal development of the instability also highlighted zones particularly active during the considered periods. The activation of the same zones has been evidenced also by the sudden increase or the tilt angle measured by tiltmeters CE03, CE04, CE07, CE08 (Fig. 14).

Nevertheless, it must be pointed out that the definition of an interval (three months in the presented case) necessarily influences the results of the analysis, as the acceleration periods not do not repeat regularly. The a priori definition of the used interval

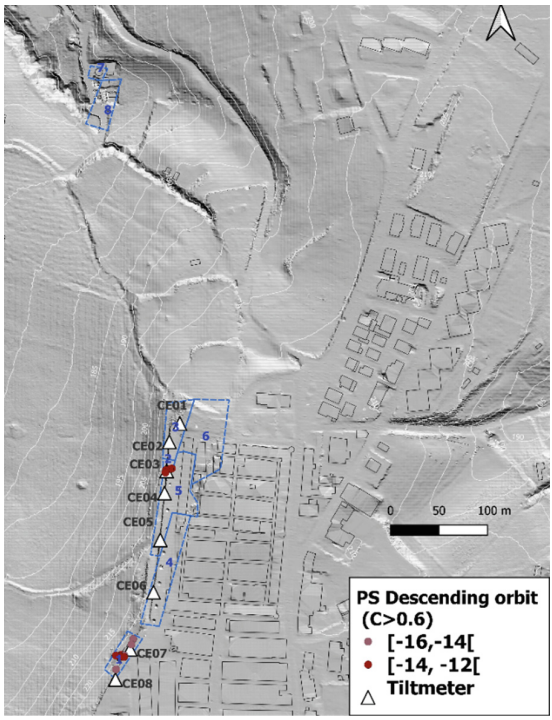


Fig. 14. Areas characterized by maximum negative displacement velocities along the LoS, with superimposition of the tiltmeters location.

may therefore have led to underestimate displacement velocity whit respect to shorter acceleration periods or overestimate it during the low velocity phases.

Until January 2023, the measurements of the tiltmetric network installed along the retaining structure indicated the absence of planimetric shift of the retaining wall. The last measurements evidence instead the non-simultaneous activation of the landslide body, which mechanisms are currently under investigation.

The outcomes of this work provided key information to the structures responsible for the management of the risk connected with the instability, and allowed the addressing of the proper design of the mitigation works. The measurements acquired by the tiltmeters constituting the early warning system, implemented after the MTInSAR analysis evidence, confirmed the peculiar trend of the phenomenon.

Future developments of this study foresee the analysis of ground topographic observations regarding the slope area underneath the town and the integration with geotechnical and geological models to gain a comprehensive understanding of the landslide evolution.

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