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INTEGRATED INFRASTRUCTURE MONITORING PROCEDURE FOR ROAD NETWORK MANAGEMENT

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ABSTRACT

This research examines the application of Interferometric Synthetic Aperture Radar (InSAR) from space for tracking and evaluating surface and structural changes in transport networks, particularly a 65 km stretch of the A16 highway in Southern Italy. The project merges various elements like the design planimetry of the infrastructure, SAR image datasets, measurements taken on-site, and an updated Landslide Inventory Map (LIM) to validate the compatibility of SAR outcomes with conventional monitoring techniques, especially inclinometers. Considering the widespread presence of erosional and gravitational events, such as landslides in this area, effective surveillance is crucial. The investigation utilizes COSMO-SkyMed imagery from 2015-2022. These data are processed via the Coherence Pixels Technique (CPT) algorithm, delivering numerous Persistent Scatterers (PSs). Inclinometers were used to record ground deformations and authenticate DInSAR products, showing alignment between the two different methodologies. The research highlights the value of DInSAR measurements for overseeing infrastructural changes caused by geological occurrences like landslides. These data could be integrated into an early warning mechanism, supporting decision-making processes for managing transport networks.

Index Terms— Interferometric Synthetic Aperture Radar (InSAR), Transport networks, Ground deformations, Landslide Inventory Map (LIM), Early warning system

1. INTRODUCTION

Road networks serve as essential arteries facilitating socio-economic growth within societies, underpinning the flow of people, goods, and services that stimulate development. To maintain these arteries in optimal condition, it is imperative to regularly monitor and evaluate any surface and structural deformations that may be caused by natural hazards or human-induced activities [1-3]. Recent technological advancements have introduced a sophisticated monitoring tool: the space-borne Interferometric Synthetic Aperture Radar (InSAR). This tool provides a unique auxiliary perspective to conventional ground monitoring systems, permitting preliminary evaluations of various phenomena. More significantly, it allows for extensive, large-scale investigations into the deformations affecting the surfaces of road networks [4-7].

This research article delves into an in-depth analysis of a 65 km segment of the A16 highway located in Southern Italy, with the objective of demonstrating the seamless interoperability of SAR results and traditional inclinometer-based monitoring measurements. The A16 highway represents a crucial transportation infrastructure in Italy, connecting the city of Naples on the Tyrrhenian coast to the Adriatic Sea, and cutting across the rugged terrain of the Campania Apennines. The region is characterized by hilly slopes with a low to medium gradient, and it is subjected to various erosional and gravitational phenomena. Landslides, in particular, are a prevalent and notable geohazard in the area [8-10].

The current ground displacement monitoring infrastructure in this area comprises 86 inclinometers installed by the infrastructure stakeholders. By leveraging the availability of detailed infrastructure design planimetry, SAR image datasets, in-situ measurements, and an updated Landslide Inventory Map (LIM), a comprehensive analysis of the highway segment was carried out [11-12]. Notably, landslides that involve large volumes of material and are characterized by slow movements can be monitored over extended periods, even using satellite monitoring techniques.

This study capitalized on the extensive availability and proven reliability of SAR data, which was processed using the sophisticated Coherence Pixels Technique (CPT) algorithm. The data utilized more recent COSMO-SkyMed images covering the period between April 2015 and September 2022.

One of the central objectives of this research is to validate the reliability of DInSAR measurements in comparison with traditional in-situ monitoring methods, such as those involving inclinometers. Given the vast quantity of available SAR data, along with its affordability and proven reliability, the approach delineated in this study could be widely employed to monitor and assess the deformation of structures impacted by geological phenomena like landslides or subsidence over time. Moreover, this wealth of data could

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be incorporated into an early warning system, serving as an invaluable tool to assist transport network managers in their decision-making processes. This would ultimately contribute to improving safety standards and maintenance practices in crucial transportation networks, promoting their longevity and serviceability.

2. CASE STUDY

In this case study, we delved into an exhaustive analysis of a 65 km segment of the A16 highway in Southern Italy. This highway, a crucial conduit connecting Naples on the Tyrrhenian coast to the Adriatic Sea, transverses the Campania Apennines. The landscape in this region is characterized by low-to-medium gradient hilly slopes, widely affected by various erosional and gravitational phenomena, with landslides being notably frequent and significant. Delving deeper into the landslide inventory, as vividly illustrated in Figure 1, it becomes apparent that a plethora of landslide classes can be observed. The official database, updated up to 2017, unveils that the most common occurrences are related to roto-translative slides and flows that involve massive volumes of material. Other types of landslides noted in the database are rapid flows, complex landslides, and diffuse deformation areas, each with its unique characteristics and implications.

Consequently, 86 inclinometers were installed by the infrastructure stakeholder for ground displacement monitoring in this section of the highway.

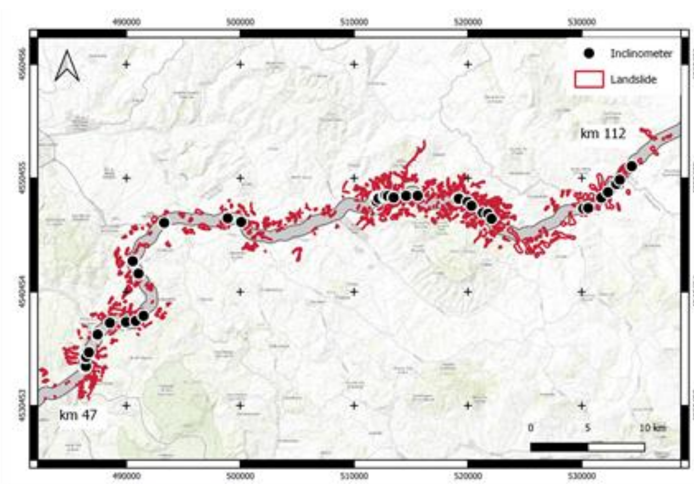

Figure 1. Landslide Inventory Map and inclinometer locations.

3. DATA SETS

This study made use of a comprehensive range of datasets to perform an in-depth analysis of a 65 km segment of the A16 highway in Southern Italy. The datasets enabled us to demonstrate the interoperability of SAR results and traditional ground monitoring measurements, such as inclinometers.

Infrastructure Design Planimetry: This data set provided the layout and design information of the highway infrastructure, which served as a vital reference during the analysis.

SAR Image Datasets: The SAR image datasets were crucial for assessing surface deformations on a large scale. The available SAR data included COSMO-SkyMed images, covering the period from April 2015 to September 2022. The COSMO-SkyMed data comprised a stack of 125 images for the ascending dataset and 85 images for the descending dataset.

In-Situ Measurements: Recorded by 86 inclinometers positioned by the infrastructure stakeholder along the highway, these measurements were instrumental in validating the DInSAR results by comparing the ground displacements recorded by the inclinometers and those observed in the SAR data.

Landslide Inventory Map (LIM): The LIM, updated to 2017, provided valuable insights into the landslide patterns in the region. The most represented classes were roto-translative slides, flows, rapid flows, complex landslides, and diffuse deformation areas.

All these datasets, when taken together, provided a comprehensive overview of the landslide deformation phenomena affecting the A16 highway.

4. METHODOLOGY

4.1. Satellite Data Processing

We acquired and processed a stack of 125 and 85 COSMO-SkyMed images for the ascending and descending geometries, respectively, covering the period from April 2015 to September 2022. These satellite products were processed through the SUBSIDENCE software with the CPT algorithm.

We applied the CPT algorithm to the processed satellite images. The CPT is a method used to identify stable radar reflectors, or Persistent Scatterers (PSs), in radar images over time. It allowed us to detect the PSs surrounding the A16 highway, which is important for understanding ground displacements in the area.

4.2. Comparing In-Situ Measurements and DInSAR Results

We evaluated the reliability of satellite measurements and validated the DInSAR products by comparing the ground deformations recorded by the inclinometers with the SAR-derived displacements. The ground deformations were projected along the Line of Sight (LoS) of satellites using the equation:

$$S_{LoS} = - S \, \mathrm{sen}\theta \cos(\alpha-\gamma) \quad (1)$$

Where:

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S_{LoS} is the projection of the ground displacement along the LoS;
S is the ground displacement recorded by the inclinometer;
θ is the satellite incidence angle (equal to 29.4° for the COSMO-SkyMed products used);
α is the inclinometer azimuth angle measured during the field acquisition;
γ is the satellite azimuth angle (heading angle);
Following the comparison, a consistency check is conducted to confirm that the displacements measured by the two different types of techniques are in agreement. This is crucial for confirming the reliability of the DInSAR measurements and ensuring the accuracy of the PS analysis, which is a valuable technique for monitoring landslide deformations.

4.3. Road Axis Monitoring and Anomalous Area Identification

After confirming the reliability of DInSAR measurements, we monitored the entire road axis for landslides and other significant ground displacements. The road axis, or the centerline of the highway, is monitored in its entirety using the validated DInSAR measurements. This monitoring allows for the detection of significant displacement rates along the entire length of the highway, which is crucial for ensuring the safety and operational integrity of the infrastructure. This step also involves the identification of anomalous areas along the highway – areas where the displacement rates are significant, but landslides are not present or where the installed instrumentation indicates irregularities. Recognizing such areas is crucial, as they may require additional monitoring instruments for a better evaluation of ground displacements, or they may signal potential issues that need further investigation.

5. RESULT AND DISCUSSION

The main crux of this study centers around the utilization of the DInSAR technique to effectively monitor a sizable stretch of 65 km on the A16 highway.
The results generated from this research are deeply rooted in an integrated methodology that combines the design planimetry of the SAR image datasets, in-situ measurements, and an updated Landslide Inventory Map (LIM).
Building on this ground-level data, satellite data processed from COSMO-SkyMed imagery (Figure 2) is merged into the mix, allowing a more comprehensive understanding of displacement patterns within the region.

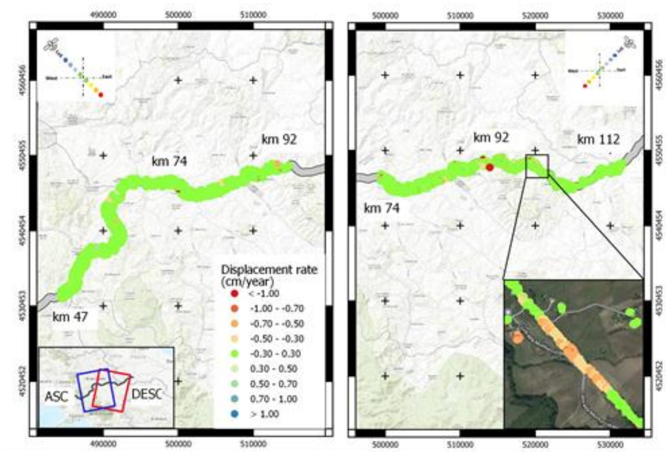

Figure 2. Mean displacement rate maps: ascending (left), descending (right).

The processed satellite data, particularly the ascending dataset, provided a significant amount of PSs, approximately 260,000, around the highway vicinity. This equates to an average of around 6,000 PS/km. On the other hand, the descending dataset presented a different pattern, identifying 80,000 PSs within the A16 buffer zone, with an average of about 2,500 PS/km. These distinctive results emphasize the importance and value of utilizing both ascending and descending geometries in SAR data analysis for a well-rounded and reliable outcome.
The results show that the displacements measured by the two different types of techniques are consistent, and the comparison of the DInSAR results and the in-situ monitoring by inclinometers confirms that the PS analysis is a valuable technique to monitor landslide deformations. This technique can provide plenty of ground measuring points with time-series deformations through the employment of high-resolution SAR imagery, also for landslides affecting infrastructures outside of urban areas. Then, checked the reliability of the DInSAR measurements in order to monitor the road axis in its entirety, was possible to highlight other areas in which the displacement rates are significant, but landslides are not present, and even installed instrumentation highlighting anomalous areas where additional instruments can be positioned for a better evaluation of ground displacements.
Also, as seen in Figure 3, during the investigation and deformation analysis with the DInSAR approach, we can use a considerable amount of PS points and find the deformation trend if we do not have any in-situ data. For example, in this figure, between 07/2020 to 03/2022, when there was a lack of information from inclinometer data, the PS point can give us insight and the displacement trend in our case study.

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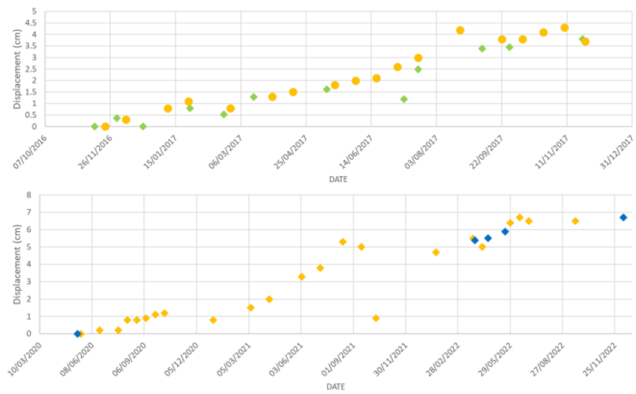

Figure 2. Comparison between the inclinometer data (green and blue dots) and PS points (orange dots) extracted in the deformation zone of A16 highway.

6. CONCLUSION

In closing, this research presents a significant contribution to the body of knowledge pertaining to the monitoring and evaluation of transport infrastructure subjected to geohazards. The methodology developed and applied, which combines SAR data analysis with in-situ monitoring techniques, has proven to be a valuable and reliable tool in evaluating surface and structural deformations along the A16 highway in Southern Italy.

The success of this integrated approach lies in its ability to capture a comprehensive picture of the situation on the ground, drawing from both satellite-based measurements and ground-based inclinometer data. The comparison and validation process presented in this research reaffirms the reliability of such an integrated approach.

The identification of anomalous areas and significant displacement rates along the road axis highlights the potential of such methodology to inform decision-making processes and the positioning of additional monitoring instruments. As a result, this approach goes beyond merely detecting issues; it facilitates proactive measures to ensure the safety and sustainability of the transport infrastructure.

In summary, this research underscores the importance of leveraging advanced satellite technology alongside traditional monitoring measurements in maintaining the safety and functionality of crucial transport infrastructure. This integrated approach represents a step forward in our collective ability to monitor, predict, and respond effectively to the challenges posed by natural hazards and human-induced activities on our transport networks.

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