13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-170

ISABHEL (Integrated SAtellite and ground-based monitoring for Bridge HEalth Lifetime assessment)

Vera Costantini[1], Bernardino Chiaia[2], Marco Civera[2], Alberto Ciavattone[4], Davide Ambrosio[3], Carlo Ranalletta[3], Emanuele Del Monte[4]; Roberta Marini[1], Paolo Mazzanti[1]
[1]NHAZCA, Italy; [2]Politecnico di Torino, Department of Structural, Geotechnical and Building Engineering (DISEG), Italy; [3]Nplus, Italy; [4]S2R, Italy;
email: vera.costantini@nhazca.com

ABSTRACT: This paper presents ISABHEL (Integrated SAtellite and ground-based monitoring for Bridge HEalth Lifetime assessment) project, which demonstrates an integrated approach to Structural Health Monitoring (SHM) by combining satellite InSAR data, contact sensors, Photomonitoring™, and Finite Element Modeling (FEM). The system is implemented on two bridges over the Po River in Turin, Italy: the Amedeo VIII and the Regina Margherita bridges. Each technology complements the others, providing a comprehensive understanding of bridge behavior. The InSAR analysis using high-resolution COSMO-SkyMed data revealed slight asymmetric deformation in the Regina Margherita Bridge, with the western lane exhibiting higher deformation rates. Contact sensors were strategically designed to be positioned based on each bridge's specific vulnerabilities, with the Amedeo VIII bridge focused on static monitoring and the Regina Margherita bridge on dynamic monitoring. The calibrated FEM models will enable prediction of structural behavior and establish critical thresholds. A web platform integrating all data sources will provide real-time visualization and alerts. This paper presents the initial results of this ongoing project funded by ESA, which will be completed in the next months.

KEY WORDS: Bridges; InSAR; Contact Sensors; Photomonitoring; Finite Element Modeling; Data Integration; 5G Communication

1 INTRODUCTION

The bridge infrastructure across Europe is aging, with many structures approaching or exceeding their design lifetime. This aging infrastructure requires consistent monitoring to ensure safety, optimize maintenance schedules, and extend its operational life. Traditional monitoring methods often rely on periodic visual inspections, which may miss early signs of deterioration and are labor-intensive [1]. Modern Structural Health Monitoring (SHM) approaches offer continuous data collection, but often focus on a single technology, providing only a partial view of the structure's condition [2]. The ISABHEL (Integrated SAtellite and ground-based monitoring for Bridge HEalth Lifetime assessment) project, funded by the European Space Agency (ESA), and with the support of the Municipality of Turin, demonstrates an innovative approach to bridge monitoring by integrating multiple technologies: satellite Interferometric Synthetic Aperture Radar (InSAR), contact sensors, Photomonitoring™, and Finite Element Modeling (FEM). This integration leverages the strengths of each technology to create a comprehensive monitoring system capable of detecting various deterioration mechanisms at different scales.

The project focuses on two river bridges in Turin, Italy: Amedeo VIII bridge and Regina Margherita bridge (Figure 1). These structures were selected due to their strategic importance, different structural characteristics, and potential vulnerability to scouring phenomena. Additionally, the Regina Margherita Bridge may be affected by slope movements on the nearby hillside.

The project aims to demonstrate how multi-technology integration can provide a more comprehensive understanding of bridge health and support evidence-based maintenance decisions.

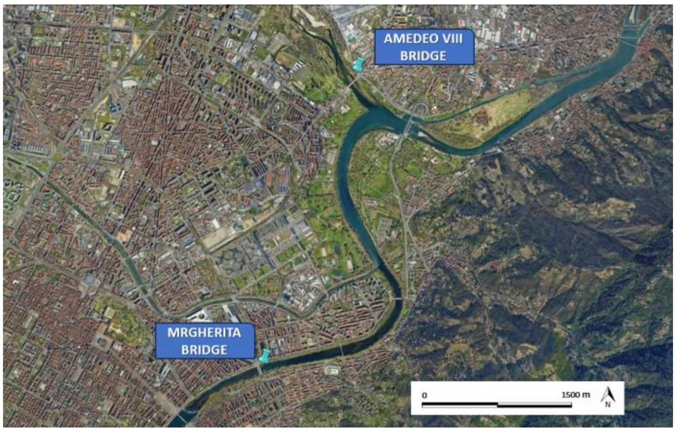

Figure 1. Location of bridges under study

2 PROJECT OVERVIEW AND METHODOLOGY

2.1 Case studies in Turin

The Amedeo VIII bridge is a reinforced concrete structure with post-tensioned cables added during a retrofit intervention in recent years. The bridge also features Gerber saddles (i.e. half-joints) which were strengthened during the same renovation (Figure 2).

The Regina Margherita bridge is a reinforced concrete structure with prestressed cables. It consists of two parallel carriageways that can be treated as separate bridges (Figure 3).

Both bridges are subject to potential scouring phenomena due to their superficial foundations. The Regina Margherita Bridge, moreover, is potentially subject to phenomena induced by slope movements on the hillside, which are difficult to perceive by on-site measurements but could be easily identified by satellite measurements over an extended area.

DOI: 10.3217/978-3-99161-057-1-170

Figure 2: Overview of Amedeo VIII bridge

Figure 3: Overview of Regina Margherita Bridge

The Amedeo VIII and Regina Margherita bridges are examples of modern infrastructures, built respectively in 1933 and between 1970-1972, constructed in reinforced concrete, and that experience substantial daily traffic (2,164 and 2,715 vehicles per day, respectively). Notably, the Regina Margherita bridge falls within Class 1 (High) attention level as per current Guidelines. The project, conceived on these typologies of infrastructures, represents an important chance to develop reliable procedures that can be applied to a significant number of similar infrastructures, which are very common on the Italian territory.

This aspect is even more important since, in the last years, significant attention has been focused on the monitoring and safety assessment of bridges, due to the recent problems that occurred on some infrastructures because of maintenance problems [1]. As evidenced by the publication by the Ministry of Infrastructure and Transport, of the document "*Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti*," in April 2020, surveillance and monitoring of bridge infrastructures should be provided especially for bridges ranked in the high attention class, which need continuous update of the structural model.

2.2 Integrated monitoring approach

In this project a comprehensive, multi-technology approach to bridge monitoring is adopted, ensuring a detailed and accurate assessment of structural health. At the core of this methodology is the integration of satellite-based and ground-based technologies, allowing for a continuous and complementary evaluation of deformation patterns and structural behavior.

The satellite-based component is represented by Interferometric SAR analysis (InSAR), which relies on high-resolution COSMO-SkyMed data to provide both historical deformation analysis and long-term monitoring of millimeter-scale displacements across the entire area of interest. This technology provides important information on long-term deformation trends and enables the detection of anomalies that might indicate structural degradation.

To complement the satellite data, a network of contact sensors is installed on the bridges, providing real-time measurements of key structural parameters. These sensors include biaxial inclinometers, triaxial accelerometers, strain gauges, displacement transducers and temperature probes, all of which contribute to acquiring data on both the static and dynamic behavior of the structures. The data collected from these sensors is transmitted via 5G technology, ensuring fast and reliable communication with the central monitoring system.

In addition to sensor-based measurements, the project incorporates an advanced Photomonitoring system. Camera installations near the bridges capture regular image sequences, which are then processed using Digital Image Correlation (DIC) and Change Detection (CD) techniques. These methods allow for the identification of visual modifications in the structure over time, facilitating the detection of potential issues such as cracks, material degradation, or unusual displacements.

To further enhance the monitoring capabilities, Finite Element Modeling (FEM) is employed to create digital twins of the bridges. These virtual models are continuously updated and calibrated using real-world data obtained from satellite observations, contact sensors, and Photomonitoring. By simulating different loading conditions and environmental factors, FEM enables predictive analysis of structural performance.

All collected data is integrated into a centralized web-based platform, which serves as the primary interface for monitoring and analysis. This platform not only visualizes the structural health status in real time but also tracks changes over time and issues alerts when predefined thresholds are exceeded. By providing an intuitive and comprehensive overview of bridge conditions, the system facilitates informed decision-making for infrastructure management, ultimately enhancing safety and optimizing maintenance efforts.

This holistic monitoring approach ensures that all critical aspects of bridge health are continuously assessed, from large-scale deformations detectable by satellite to localized structural issues identified through sensor data and image analysis. The combination of these technologies provides a robust framework for long-term monitoring and early warning capabilities, supporting proactive maintenance and extending the lifespan of the infrastructure [2,3,4].

DOI: 10.3217/978-3-99161-057-1-170

3 CONTACT SENSORS CONFIGURATION

3.1 Monitoring strategy and sensor selection

Based on field inspections and analysis of bridge documentation, the project implemented a differentiated monitoring approach for the two bridges. The Amedeo VIII bridge focuses on static monitoring, while the Regina Margherita bridge incorporates both static and dynamic monitoring. This differentiation is due to the different structural characteristics and vulnerabilities of each bridge. The contact sensor system, developed by Nplus, integrates IoT-enabled sensors with advanced data analytics to provide a comprehensive assessment of bridge health. The selection criteria included sensitivity, durability, reliability, and suitability for the specific monitoring objectives of each bridge.

The Vittorio Infrastructure system by Nplus employs a wired architecture with a 2 Mbit/s digital data bus, ensuring 24/7 reliability in power and data acquisition. The system integrates various sensors connected via a fiber optic backbone, which also powers the devices.

3.2 Regina Margherita bridge sensor layout

The Regina Margherita Bridge, constructed between 1970 and 1972, spans the Po River in Turin, Italy. It is a modern three-span arch bridge with a total length of 123.0 meters and runs primarily along a North-South axis.

The structure consists of two separate half-bridges, one for each carriageway, which are structurally independent and connected only at the mid-lane. This 3-meter-wide section between the decks was originally a tram line, later became a recreation park, and is currently a green area.

The bridge is made of prestressed reinforced concrete, while the decks are reinforced concrete box girders with variable height and six webs. They rest on steel-made fixed bearings on the south abutment and double-pendulum roller bearings on the north abutment and piers.

The piers lie on reinforced concrete caisson foundations that were sunk by self-weight rather than deep foundations, which makes the bridge susceptible to scouring and classifies it as high hydraulic risk, according to Italian guidelines.

The bridge was designed with spans ballasted with lean concrete and tie rods anchored in rock at the two abutments to reduce total downward deflection at the midspan.

For this bridge, both static and dynamic monitoring were implemented. The sensor layout was designed to detect potential scour-related issues using inclinometers and assess the deck's load-bearing capacity through accelerometers and strain gauges (Figure 4). While inclinometers and strain gauges monitor static behavior, accelerometers analyze dynamic behavior, providing a comprehensive assessment of the bridge's structural health.

- Inclinometers/accelerometers installed on piers and at deck mid-spans and quarters, respectively to:
  - Measure static rotations to check plastic drift and reconstruct the deformed span
  - Measure accelerations to perform Operational Modal Analysis (OMA), check mode drift, and identify natural frequencies, mode shapes and damping

- Strain gauges at mid-spans to monitor axial deformation, which can indicate excessive loading, prestressing cable relaxation, or changes in restraint effectiveness
- Temperature sensors on different spans to correlate environmental conditions with structural responses.

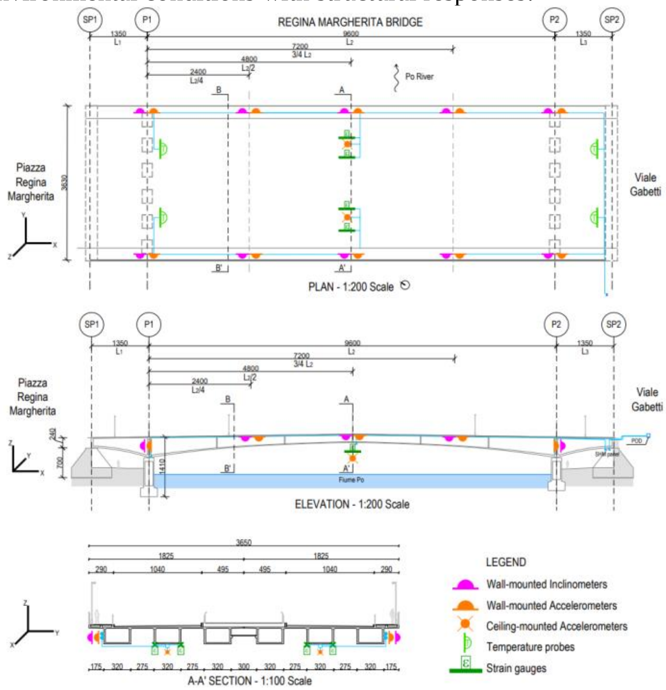

Figure 4: Contact sensors configuration for Regina Margherita Bridge

3.3 Amedeo VIII bridge sensor layout

The Amedeo VIII Bridge, constructed in 1933, crosses the Stura River, a major tributary of the Po River, which it meets in Turin. This five-span bridge has a total length of 153.3 m, and its main axis lays in a southwest-to-northeast direction.

The bridge has a single carriageway, consisting of two lanes in each direction plus two large walkways - one on each side. The girder bridge has a regular grid of reinforced concrete (R.C.) transverse and longitudinal beams (these latter ones with variable thickness along the bridge's main axis) with the addition of post-tensioned cables during a recent structural retrofit intervention.

The deck is simply supported on the R.C. piers and clamped at the two abutments. On the second and fourth spans are located two half joints (i.e. the so-called Gerber saddles), which carry two simply supported half-spans.

Exactly as in the case of the Regina Margherita Bridge, all piers lie on self-sunk R.C. caisson foundations, not deep foundations. For the same reasons as before, this classifies it as high hydraulic risk according to Italian guidelines. For the Amedeo VIII bridge, static monitoring was preferred in order to track displacements and rotations (Figure 5). The sensor configuration includes:

- Biaxial inclinometers installed on piers and deck span extremes to monitor:
  - Static rotations of individual spans to check plastic drift
  - Static rotations of piles to check differential settlement
  - Rotations of Gerber saddles to check for potential failures

DOI: 10.3217/978-3-99161-057-1-170

- Strain gauges installed on Gerber saddles to monitor expansions and detect potential saddle failures
- Temperature sensors installed on different spans to correlate environmental conditions with structural responses.

This configuration focuses on the bridge's main vulnerabilities: scouring phenomena (monitored through inclinometers) and the Gerber saddles (monitored through inclinometers and strain gauges).

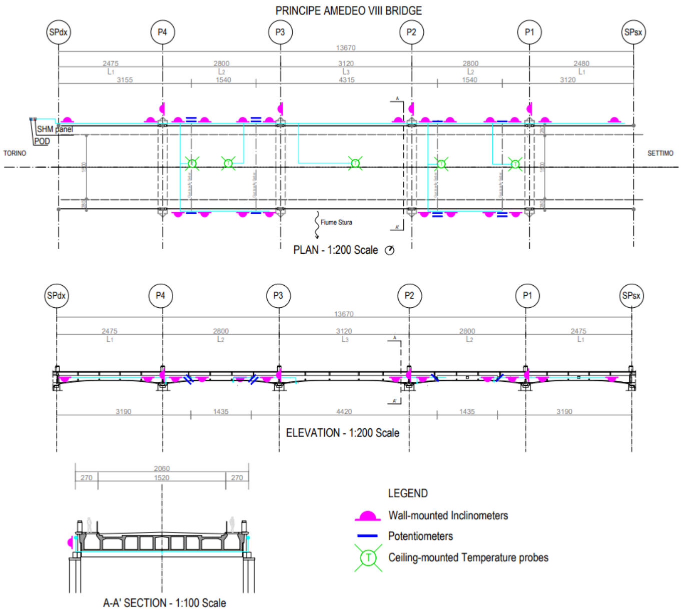

Figure 5: Contact sensors configuration for Regina Margherita Bridge

4 A-DINSAR ANALYSIS

4.1 Satellite radar interferometry technique

In this study, the Advanced Differential Synthetic Aperture Radar Interferometry (A-DInSAR) technique [5] is used to analyze historical ground displacement rates within the Turin municipality. A-DInSAR detects surface deformations by analyzing phase differences between successive radar satellite observations of the same area. These variations in the RADAR signal phase, reflected from objects on the Earth's surface, are directly correlated with ground movement, enabling the generation of high-resolution deformation maps [6,7]. Specifically, this technique is widely utilized for studying the temporal evolution of ground displacement of Persistent Scatterers (PS), which are objects within the SAR resolution cell (3x3 m2 for CSK) that maintain consistent reflectivity over time [8].

The applied InSAR methodology follows the Persistent Scatterer Interferometry (PSI) approach, as described in reference articles [9] and [10]. The PS-InSAR technique extracts deformation information from an interferometric stack of SAR images, allowing for detailed pattern analysis. SAR datasets from the Cosmo-SkyMed (CSK) mission, operated by the Italian Space Agency (ASI), were utilized, which has provided archived data since 2009 and are free for research purposes. The CSK system is equipped with an X-band sensor (about 3.1 cm wavelength) that allows for millimetric displacement measurement precision. In STRIPMAP mode, it offers a spatial resolution of 3m×3m. Over Italy. The revisiting time is 16 days with occasional gaps due to the dual use of the constellation for civilian and military applications.

For this study, a total of 460 SAR images were processed covering the period from 2011 to 2024, acquired in ascending and descending orbital geometries:

- Ascending orbit: 231 Single Look Complex (SLC) images acquired between January 18, 2011, and August 23, 2024.
- Descending orbit: 229 SLC images acquired between May 18, 2011, and September 24, 2024.

The A-DInSAR derived deformation rate values (expressed in millimeters per year) were estimated relative to a designated reference point. To ensure accuracy, our results were calibrated and validated using displacement data from the GNSS station located in the municipality of Turin.

To evaluate the reliability of our results, an error analysis was conducted, estimating the standard deviation of deformation rates, and assessing temporal coherence levels, considered only the points with temporal coherence up to 0.4.

In addition, complementary remote sensing techniques were integrated, including ground-based leveling data, to cross-validate our results. The Turin municipality is characterized by complex subsurface conditions, including sandy-gravelly alluvium and clayey alluvial soil, which contribute to varying deformation patterns. These geological factors were taken into account in our analysis to improve the interpretation of observed displacement trends.

4.2 Post-Processing and Analysis of Satellite Interferometry Data

The post-processing of satellite interferometry data is carried out using the PS-ToolBox Suite, developed by NHAZCA S.r.l. and integrated into QGIS. This suite enables the visualization of time series, decomposition of line-of-sight displacements, and the creation of various data representations to identify significant structural movements.

The vector decomposition process of the data allows the generation of velocity maps for the Synthetic Measurement Points (SMPs) in both vertical and horizontal (East-West) directions. These maps are derived from the decomposition of measurements along the sensor's line of sight (LOS) obtained through both ascending and descending orbital geometries.

It is essential to note that displacement and velocity measurements are calculated along the sensor's LOS. Therefore, the detected displacements represent the projection of actual displacements along the sensor-target line. Indeed, the observed displacement is the combination of the vertical and slightly east-west movement. Combining the observation from two looking geometries it's possible to decompose the signal along the vertical and horizontal components.

The data vector decomposition process was performed using proprietary algorithms to extract displacement vectors in both horizontal and vertical directions. The study area was discretized into hexagonal cells with a 5 m radius, arranged on a regular grid. The results were displayed only for cells containing at least one measurement point for both orbital

 DOI: 10.3217/978-3-99161-057-1-170

geometries, referred to as "Synthetic Measurement Points" (SMPs).

PS times series tool allows the interactive visualization and analysis of time series derived from satellite datasets, providing a detailed representation of the displacement evolution over time. The analysis of this time series helps identify patterns of progressive subsidence, seasonal variations, or sudden displacement changes, which could indicate structural anomalies or external influences.

The Interferometric Section tool creates interferometric sections using data analysis from different orbital geometries. The sections follow the road alignment and intersect the Measurement Points (MPs) of the monitored bridges, allowing the visualization of displacement distribution along a topographic profile.

4.3 A-DInSAR Results

The results of the A-DInSAR analysis are presented through maps overlaid on orthophoto-based backgrounds, illustrating the annual average velocities of the measurement points (MP) across the study area, including the two bridges under investigation. A color scale, expressed in mm/year, is used to represent the average displacement velocity along the satellite line of sight (LOS): colors ranging from yellow to red indicate movement away from the sensor, while shades from cyan to blue denote movement towards it. Green areas correspond to measurement points with negligible or non-significant displacement variations, with an estimated instrumental accuracy of approximately ±1.0 mm/year. The analysis provided a well-distributed spatial coverage of MPs across the entire study area in both ascending and descending geometries, ensuring redundant observation of potential deformation processes. A higher density of MPs is observed in urbanized areas, whereas a lower density is found in regions with dense vegetation or agricultural land.

A detailed analysis follows, focusing on the bridges, where time series of displacement for some measurement points, based on the A-DInSAR analysis, are shown for both ascending and descending geometries, plotted with the cumulated rain over time.

The final products are represented by velocity maps of the measurement points (MP) in the vertical and horizontal directions. These maps are obtained from the vector decomposition of measurements along the satellite line of sight (LOS) for the MP data collected in both ascending and descending orbital geometries.

4.4 REGINA MARGHERITA BRIDGE Results

The Regina Margherita Bridge exhibits moderate deformation in the area where it is structurally stable, characterized by a localized movement at the midspan that is clearly visible in both satellite acquisition geometries. In Figure 6, the A-DInSAR analysis for the descending geometry shows that, while the bridge's abutments and piers at the ends remain stable, there is a non-negligible deformation (>2 mm/yr) in the LOS direction, away from the sensor. In this geometry, the western carriageway seems to be more affected by the deformation, but possibly this is an artefact due to the satellite's line of sight. The up-down (UD) component, instead, is limited to <2 mm/yr. However, from an engineering perspective, considering the uncertainties associated with SAR technology, these outcomes will require further analyses to be accepted beyond any reasonable doubt. Figure 7 presents three representative time series for this carriageway, showing that measurement point MP2 at midspan accumulates up to 50 mm of displacement over the analyzed period.

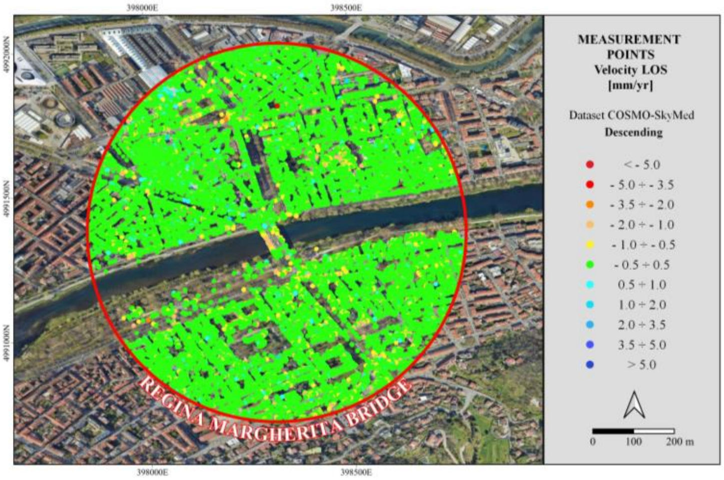

Figure 6 Velocity map of Measurement Points (MPs) obtained from A-DInSAR analysis in descending geometry for the Regina Margherita bridge area.

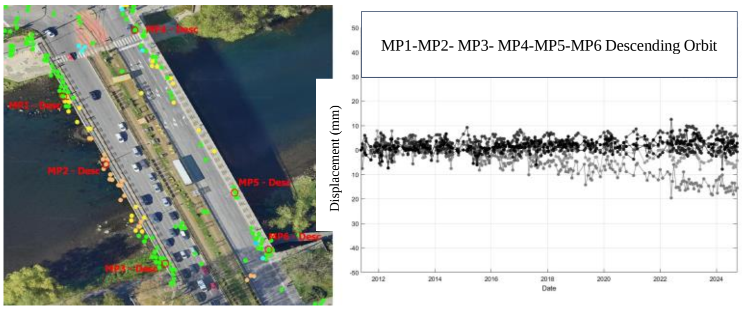

Figure 7 Time series of three measurement points for descending orbit on Regina Margherita bridge

Figure 8 shows the results from the ascending geometry, which display a deformation with rates of 2–3 mm/yr on both carriageways.

DOI: 10.3217/978-3-99161-057-1-170

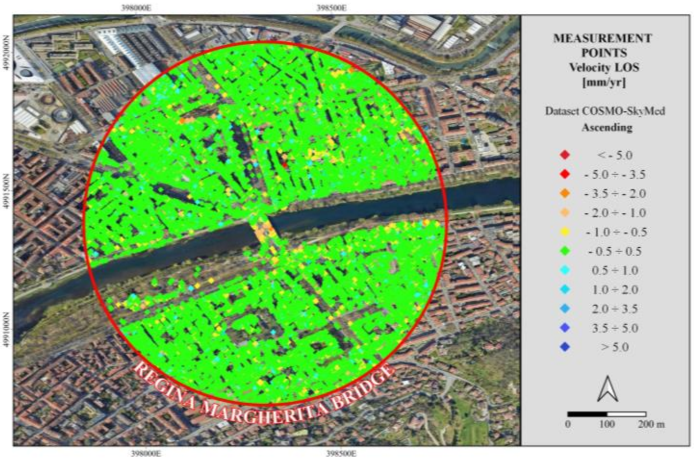

Figure 8 Velocity map of Measurement Points (MPs) obtained from A-DInSAR analysis in ascending geometry for the Regina Margherita bridge area.

From vector decomposition of the two LOS analyses, velocity maps for the vertical and horizontal components of displacement in the bridge area were produced (Figure 9).

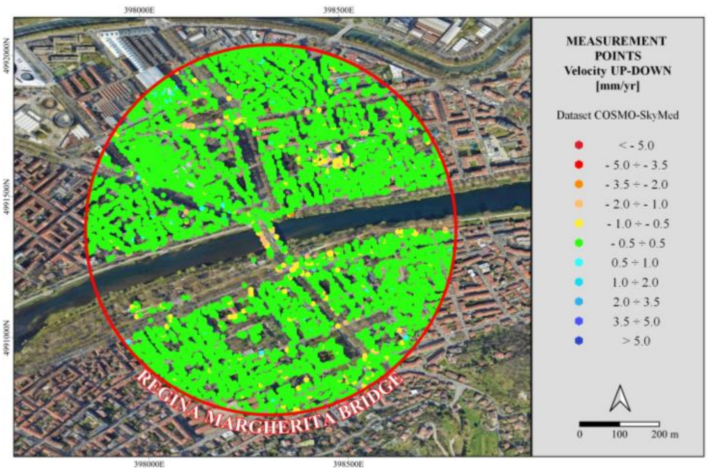

Figure 9 Velocity map of the Synthetic Measurement Points in vertical direction for Regina Margherita Bridge

The most representative outputs from the complete post-processing analysis of the satellite data are presented in Figure 10, which shows the cumulative vertical displacement along both the facade and plan view of the bridge, sampled at 5-meter intervals, to detail the deformative behavior in space and time. The interferometric section, which illustrates the evolution of the bridge's deformation over time and space, is presented in Figure 11.

4.5 AMEDEO VIII BRIDGE Results

The Amedeo VIII Bridge exhibits deformation values within the stable range along its entire length, while the surrounding area shows minimal deformation. In figure 12, the descending geometry A-DInSAR analysis confirms that the bridge remains stable throughout its span, in contrast to adjacent areas that display displacement rates on the order of -2 mm/yr. Moreover, the time series presented in figure 13 clearly delineates the

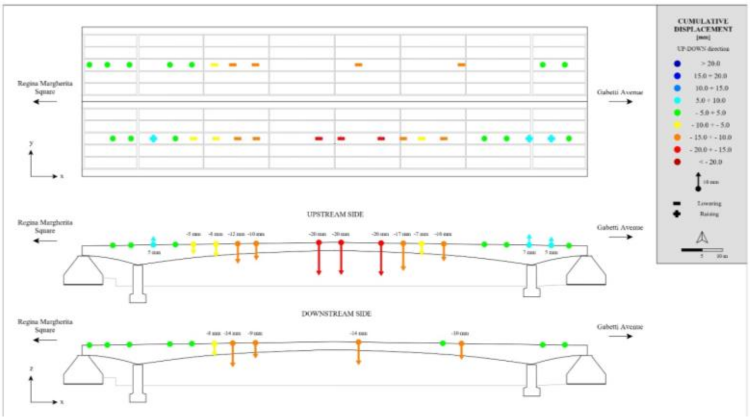

Figure 10 Cumulative vertical displacement on Regina Margherita Bridge

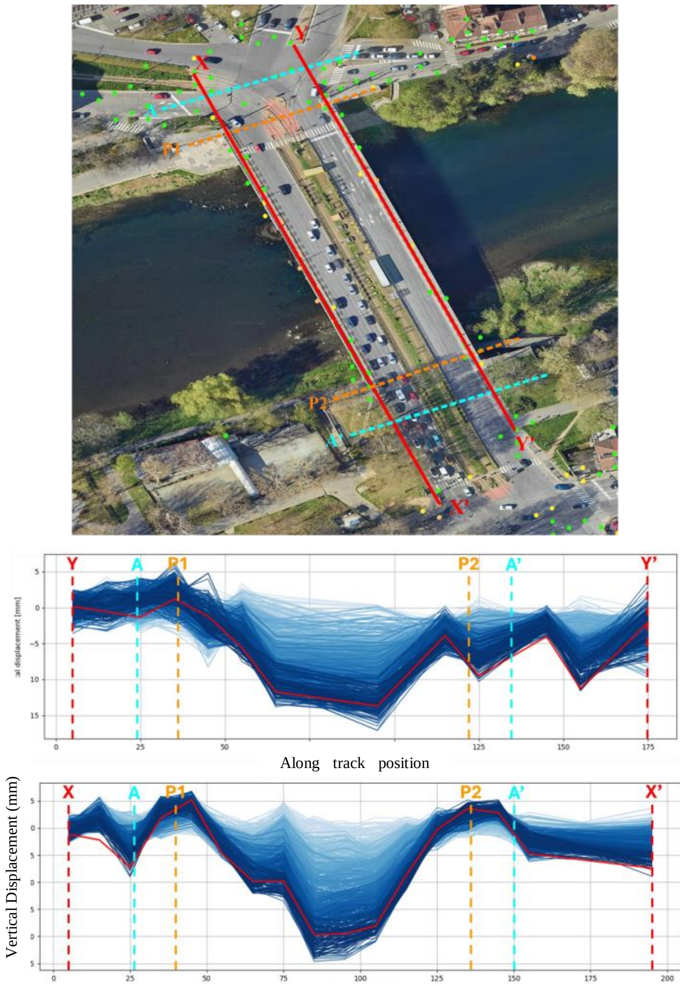

Figure 11 Interferometric section over the vertical deformation along the longitudinal path double way of the Regina Margherita bridge.

DOI: 10.3217/978-3-99161-057-1-170

seasonal cyclic trend, with an average displacement of approximately zero.

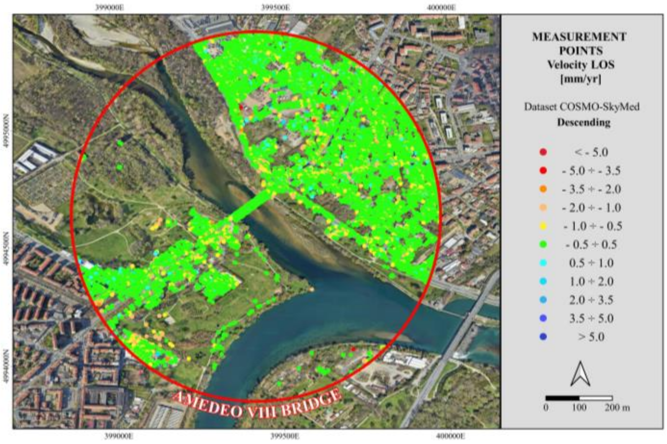

Figure 12 Velocity map of Measurement Points (MPs) obtained from A-DInSAR analysis in descending geometry for the Amedeo VIII bridge area.

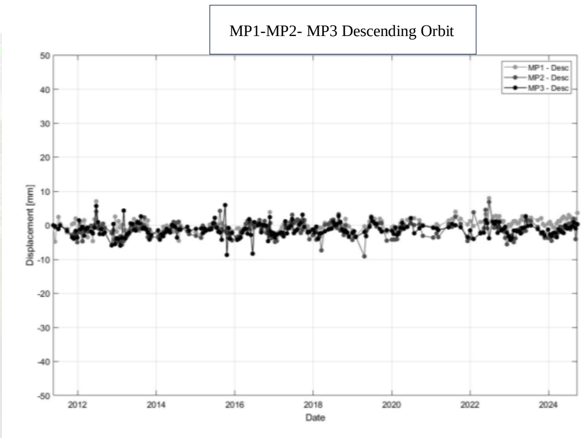

Figure 13 Time series of three measurement points for descending orbit on Amedeo VIII bridge

From the vector decomposition of the two LOS analyses, velocity maps for the vertical and horizontal components of displacement in the bridge area were produced, as shown in figure 14 and 15.

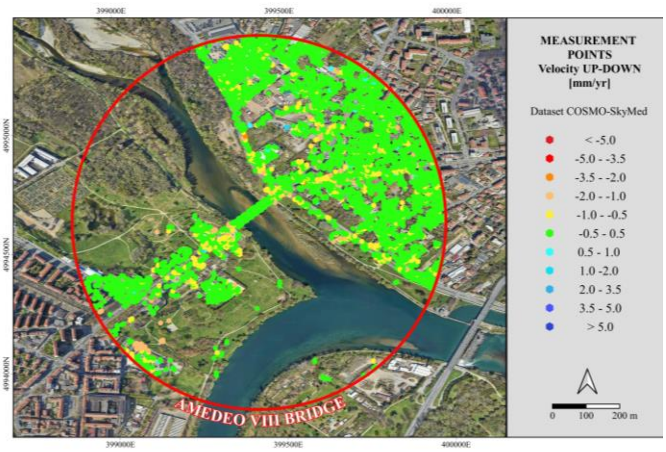

Figure 14 Velocity map of the Synthetic Measurement Points in vertical direction for Amedeo VIII bridge

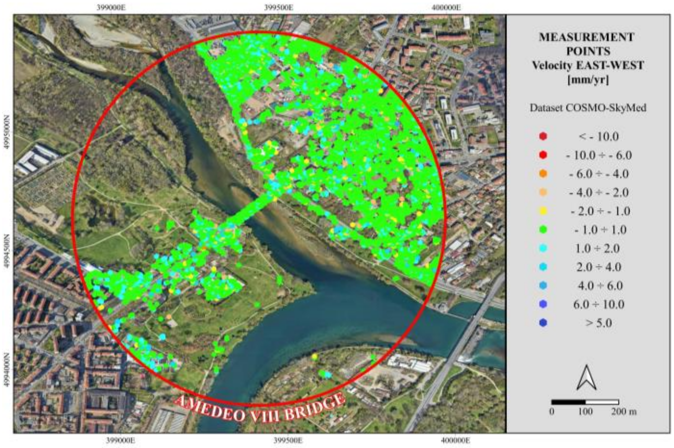

Figure 15 Velocity map of the Synthetic Measurement Points in horizontal direction for Amedeo VIII bridge

Finally, the most representative outputs from the complete post-processing analysis of the satellite data are presented in Figure 16, which shows the cumulative vertical displacement along both the facade and plan view of the bridge, sampled at 5-meter intervals, to detail the deformative behavior in space. The interferometric section, which illustrates the evolution of the bridge's deformation over time and space, is presented in figure 17.

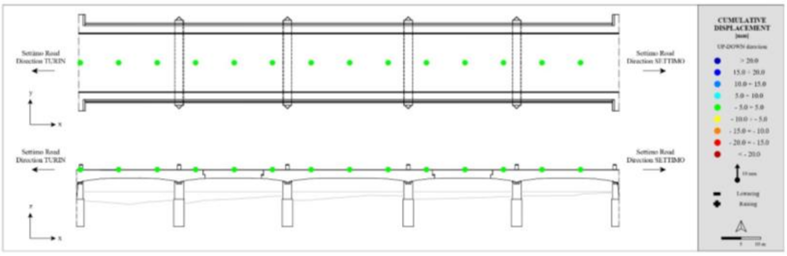

Figure 16 Cumulative vertical displacement on Amedeo VIII bridge

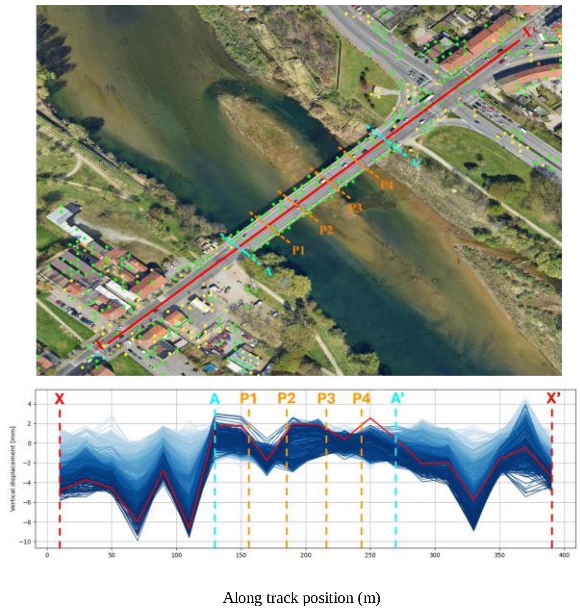

Figure 17 Interferometric section over the vertical deformation along the longitudinal path of the Amedeo VII bridge

DOI: 10.3217/978-3-99161-057-1-170

It is clear from the interferometric sections, which illustrate the deformation behavior over time and space, that the bridge is stable, both the piers and the deck show minimal deformation.

5 PHOTOMONITORING

5.1 Introduction to technology

Photomonitoring™ is an innovative monitoring technique that can exploit any kind of raster data. Photomonitoring™ is based on the identification and analysis of terrain elements and structures and their possible variations through examining images acquired at different times. The analysis uses Digital Image Correlation (DIC) and Change Detection (CD) techniques implemented through NHAZCA's proprietary IRIS software. IRIS is conceived to work with terrestrial, aerial and satellite imagery of any datatype (Optical, Thermal, Near-Infrared, etc.). The technique allows to reach millimeter accuracy in displacement monitoring and can be used separately or combined with other monitoring systems [11,12].

5.2 Monitoring strategy

In the ISABHEL project, the images will be acquired by cameras installed at the site.

For both bridges, MOBOTIX cameras with dual-lens configuration were deemed as the optimal choice: a wide-angle lens providing a global view and a telephoto lens focused on a specific pier (Amedeo bridge) or for monitoring crack evolution (Regina Margherita bridge).

On Amedeo bridge a single MOBOTIX M73 camera will be installed. The primary focus for the Amedeo VIII bridge is to monitor hydraulic action that can cause scouring of the piers and overall movement of the structures. The camera will be installed on the west riverbank, approximately 60 meters from the central area.

In particular, the wide-angle lens will capture a big part of the bridge, including all piers, providing an overview of the structure and detecting movements through DIC analysis. A telephoto lens will target a specific pier to monitor material accumulation (change detection analysis) and scouring caused by river flow (displacement of the pier).

For Regina Margherita bridge, a MOBOTIX S74 camera will be installed. The main monitoring objectives for the Regina Margherita bridge are crack detection, structural deformation, scouring and material accumulation at the base of the piers, and monitoring during high water levels or flooding conditions. The telephoto lens will be pointed at the nearest span to monitor the evolution and appearance of cracks (change detection). The wide-angle lens will detect displacements of the entire structure, with particular attention to the middle section.

5.3 Image acquisition and analysis workflow

For both bridges, image acquisition follows these specifications: Static images captured every 5 minutes for continuous monitoring; Automated trigger mechanism that switches to video recording (30 frames per minute) when significant changes are detected; Data processing using the IRIS software, which compares images within a 10-15 minute buffer to select the best quality for analysis.

The analysis workflow includes the following tasks:

- Feature Monitoring: Images processed using the IRIS software to assess changes in targeted areas, particularly cracks in the nearest arch and scouring at the base of piers; continuous comparison of images within a 10-15 minute buffer to select the best quality for analysis.
- Change Detection: Identifies structural changes while eliminating noise caused by lighting, water turbulence, or environmental conditions; specific attention to crack propagation and material accumulation.
- Displacement Analysis: Determines the extent and direction of structural movement, especially in the arches and piers. The system continues analysis until the structure returns to a stable state.

Figure 18: Example of monitoring of cracks evolution in a viaduct; the image below shows the result of change detection analysis.

6 FINITE ELEMENT MODELLING AND THRESHOLDSDEFINITION

6.1 FEM generation

Before beginning the bridge's structural modelling, two essential preliminary activities need to be conducted. First, all technical documentation concerning the bridge's structural aspects were gathered. Second, on-site inspections were performed to evaluate the current site conditions, confirm that the built structure matches the original designs, assess the current state, and collect other important observations.

The two bridge models were developed using CSI Bridge, a software specialized in the structural analysis of bridges, compliant with regulations for moving loads. The models enable linear analyses for comparison with data from contact-based sensors to be installed.

The modelling evolved from a simplified "frame" model, with the superstructure condensed into a single element, to a more detailed "shell" model, discretizing the deck with two-dimensional elements for greater accuracy, also allowing the modelling of the complex layout of the prestressed cables.

The validation phase has begun, with progressive verification of the models' accuracy and stability. This iterative approach ensures that potential discrepancies are addressed early, enhancing the robustness and reliability of the results as the

DOI: 10.3217/978-3-99161-057-1-170

project advances into more sophisticated modelling phases. As the monitoring campaign progresses, the experimental data will be integrated into the digital twins, minimizing error propagation in critical areas of structural performance and enhancing the models' predictive capabilities for real-world scenarios. In later work stages, the numerical model is thought to be updated with material testing results and with the results from the ongoing monitoring system. Creating a reliable model that delivers consistent results is essential to be able to compare and potentially reproduce the phenomena detected through satellite monitoring (fig. 19).

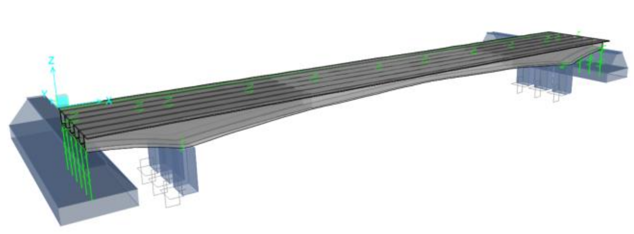

Figure 19: FEM model of the Regina Margherita bridge

6.2 SHM Parameters and Thresholds

The SHM system monitors several key parameters that indicate bridge structural health:

1. Static Parameters:
   - Rotational measurements from inclinometers at pier bases, deck spans, and Gerber saddles
   - Displacement measurements from transducers at expansion joints and Gerber saddles
   - Strain measurements from gauges at mid-spans
   - Deformation maps and displacement values from InSAR and Photomonitoring™
   - Surface Damage (Cracks Evolution/Appearance) through Photomonitoring
   - Debris material accumulation through Photomonitoring
2. Dynamic Parameters:
   - Acceleration measurements for modal analysis (natural frequencies, mode shapes)
   - Vibration characteristics in response to traffic and environmental loads
3. Environmental Parameters:
   - Temperature measurements for correlation with structural responses
   - Environmental conditions that might affect monitoring results

A multi-level threshold approach has been established to evaluate the monitored parameters:
1. Level 1 (Operational Conditions): Defined according to evaluations based on preliminary models. This represents normal operational conditions.
2. Level 2 (Statistical Deviation): Based on a data-driven model trained on the first period of continuous monitoring. This represents a significant (but not ultimate) deviation from normal behavior.
3. Level 3 (Ultimate Limit State): Derived from numerical simulations of the FEM models, representing the expected ultimate limit state before structural failure.

These thresholds are calibrated using the multi-source data from the integrated monitoring system. The temperature data is particularly important, as understanding the structural behavior induced by temperature variations is crucial for distinguishing normal responses from anomalies.

7 WEB PLATFORM

The ISABHEL web platform has been designed to provide a seamless, real-time interface for infrastructure monitoring, offering a user-centric approach to data visualization and interaction. Built using Next.js, the front-end ensures high performance through server-side rendering and static site generation, enhancing both responsiveness and search engine optimization. The modular, component-based architecture leverages React, allowing for reusability and scalability across various interface elements.

A key feature of the platform is its interactive dashboard, which aggregates real-time structural data from multiple sources, including contact sensors, Photomonitoring cameras, and satellite-based SAR analysis. The dashboard dynamically updates through WebSockets, ensuring that users have immediate access to the latest structural health indicators (figure 20).

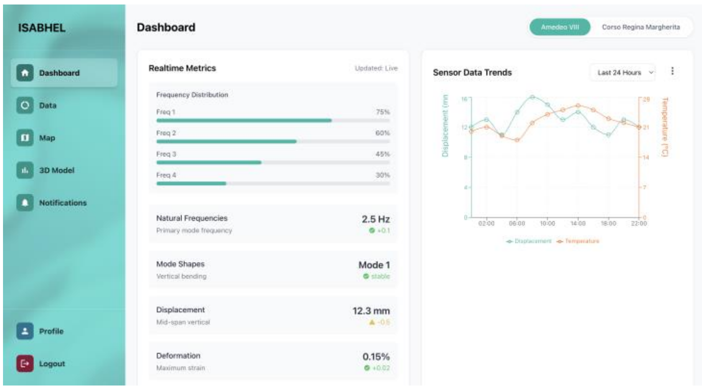

Figure 20: Dashboard of the web user interface

Another core component is the interactive GIS map, which integrates geospatial data through TileServerGL. This feature enables precise visualization of deformation patterns, historical trends, and real-time alerts. Users can navigate the bridge structures in detail, overlaying sensor readings and risk assessments to gain a comprehensive understanding of potential vulnerabilities.

To further enhance the analysis capabilities, the platform incorporates an advanced 3D bridge model rendered using WebGL technologies such as Three.js. The 3D model of the monitored bridge will be presented with a series of "traffic lights" to highlight any anomalies, using the three standard colors (green, orange, red) depending on whether the signal exceeds the predefined thresholds. "Local" traffic lights will be placed directly at the sensor's location (for example, the rotation of a pile or the movement of a Gerber saddle), while "global" traffic lights could refer to analyses at the entire structure level (such as generalized movement of the bridge,

 DOI: 10.3217/978-3-99161-057-1-170

variation in the fundamental vibration periods, etc.), helping the end user understand the nature of any anomalies (21).

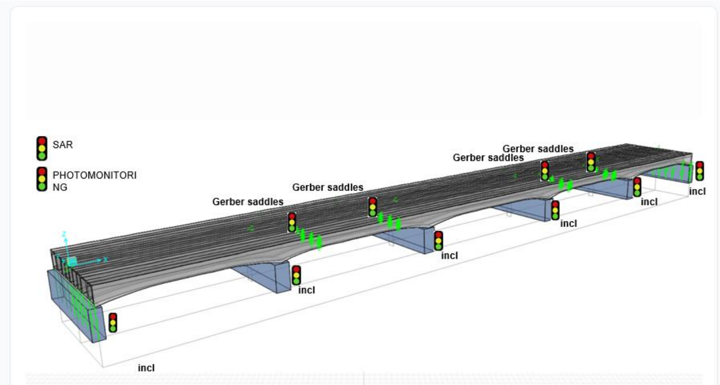

Figure 21: 3D model viewer with color-coded traffic lights

The design choices behind the ISABHEL front end prioritize usability, speed, and scalability. The use of Supabase for database management and authentication streamlines data retrieval and ensures secure access to user-specific functionalities. Additionally, the real-time notification system provides immediate alerts for threshold breaches, ensuring that stakeholders can take timely action when necessary.

8 CONCLUSIONS

The work is in its initial phase and ground-based acquisition have not started yet. However, thanks to an in-depth study of raw FEM models and based on A-DInSAR results, first-level thresholds for the bridge's structural health parameters have been estimated, which will need to be confirmed during monitoring. Based on the A-DInSAR analysis, the Regina Margherita Bridge shows localized deformation at midspan, while its abutments and piers remain stable. In contrast, the Amedeo VIII Bridge exhibits minimal deformation throughout its entire structure, with measurements remaining within the stable range (±1.0 mm/year) and displaying only seasonal cyclic variations with average displacement of approximately zero.

9 REFERENCES

[1] M. Aimar, M. Civera, S. Foti, and B. Chiaia, “Preliminary Insights from Surveys of Bridges at High Scouring Risk in West Piedmont,” in II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24), Genoa, 2024.
[2] Miccinesi, L., Giacomelli, G., Viviani, F., & Pieraccini, M. (2023). "Bridge Safety Monitoring Using Satellite and Multi-Technology Ground-Based Approaches in Italy." Journal of Bridge Engineering, 28(3), 04022094.
[3] Bonfiglioli, B., Pascale, G., & Pezzetti, F. (2020). "Digital image correlation and digital twin for bridge monitoring: Benefits and limitations." Structure and Infrastructure Engineering, 16(12), 1768-1784.
[4] Calvi, G. M., Moratti, M., O'Reilly, G. J., Scattarreggia, N., Monteiro, R., Malomo, D., & Pinho, R. (2019). "Once upon a time in Italy: The tale of the Morandi Bridge." Structural Engineering International, 29(2), 198-217.
[5] Hanssen, R. F. (2001). Radar interferometry: data interpretation and error analysis (Vol. 2). Springer Science & Business Media.
[6] Wang, S., Mei, L., Liu, R., Jiang, W., Yin, Z., Deng, X., & He, T. (2024). Multi-modal fusion sensing: A comprehensive review of millimeter-wave radar and its integration with other modalities. IEEE Communications Surveys & Tutorials.
[7] Hamzaoui Y., Civera M., Miano A., Bonano M., Fabbroncino F., Prota A. and Chiaia B. Hierarchical Clustering and Small Baseline Subset Differential Interferometric Synthetic Aperture Radar (SBAS-DInSAR) for Remotely Sensed Building Identification and Risk Prioritisation. *Remote Sens.* 2025, *17*(1), 128;
[8] Ferretti, A., Prati, C., & Rocca, F. (2002). Permanent scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1), 8-20.
[9] Kampes, B. M. (2006). Radar interferometry (Vol. 12). Dordrecht, The Netherlands: Springer.
[10] A. Ferretti, C. Prati, and F. Rocca, “Permanent scatterers in SAR interferometry,” IEEE Trans. Geosci. Remote Sens., vol. 39, no. 1, pp. 8–20,Jan. 2001
[11] Cosentino, A., Brunetti, A., Mazzanti P., Photomonitoring as a Tool for Monitoring Landslides: A Technology within Everyone’s Reach Journal of transportation Research board. August 28, 2024
[12] Mastrantoni G., Santicchia G., Cosentino A., Molinari A., Marmoni G.M., Mazzanti P. 2024. “Automatic photomonitoring analysis for spatiotemporal evaluation of rockfall failure hazard”. Engineering Geology Volume 339, September 2024, 107662,

