Bridge monitoring and assessment by high-resolution satellite remote sensing technologies

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ABSTRACT

Satellite Remote-Sensing has been successfully applied for detection of natural-hazards, (e.g. seismic events, landslides and subsidence) and transport infrastructure monitoring over the last few years. Persistent Scatterer SAR Interferometry (PSI), is a satellite remote sensing technique able to measure ground displacements over the time. More specifically, the PSI technique is an evolution of the DInSAR technique and it is based on a statistical multi-temporal differential interferogram analysis. This allows to determine coherent stable-pixels over a data-stack of SAR images, in order to identify potential ground displacements. This study aims at demonstrating the potential of the PSI technique as an innovative health-monitoring methodology for the structural integrity of bridges. For this purpose, X-Band COSMO-SkyMed images provided by the Italian Space Agency (ASI) were acquired and processed in order to detect structural displacements of the Rochester Bridge in Rochester, UK. Outcomes of this investigation outlined the presence of various PSs over the inspected bridge, which were proven useful to achieve a more comprehensive monitoring methodology and to assess the structural integrity of the bridge. This research paves the way for the development of a novel interpretation approach relying on the integration between remote-sensing technologies and on-site surveys to improve upon current maintenance strategies for bridges and transport assets.

Keywords: Remote Sensing; Non-destructive assessment; Persistent Scatterer Interferometry (PSI); PSI monitoring; Bridge monitoring, X-Band, COSMO-SkyMed, multi-temporal InSAR

1. INTRODUCTION

Bridges and road networks are exposed to a variety of threats that can affect their operations and structural integrity [1]. Recent unexpected collapses and failures of bridges underline the need for an effective structural monitoring, particularly for bridges made of reinforced concrete. These can deteriorate faster than the time required for rehabilitation, strengthing, or replacement.

Furthermore, several infrastructures built between the 1960s and 1970s are now considered as structurally deficient by the current design standards. Effective monitoring is therefore strategic to identify structural problems and critical areas at an early stage, reducing maintenance costs and preventing collapses and catastrophic events to the public safety.

On the other hand, structural problems in bridges can cause budget concerns to the administrations, leading to economic consequences at local or national level. One dramatic example is the Polcevera Viaduct in Genova, Italy, also known as the "Morandi Bridge", that collapsed in August 2018 [2-3] and caused several victims and consequences on the local and national viability. This disaster caused a major political debate outlining the critical state of transport infrastructure in Italy and raised wider enquiries about the condition of bridges across Europe [4].

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To this extent, it is evident that the monitoring of the actual conditions of the existing bridges is a priority for asset administrations in order to guarantee structural integrity, safety of the operations and preventing damage and deterioration prior to maintenance or even catastrophic failure or structural collapses.

Nowadays, the development of a fully-comprehensive monitoring system for the evaluation of endogenous and exogenous events is still an open issue. Consequently, the first step in monitoring a structure is to identify a set of information for the development and calibration of consistent engineering models. This allows to identify potential risks and critical areas and to assess the conditions of the surrounding environment.

In this context, various sensors and non-destructive testing (NDT) techniques are available for the assessment and the health monitoring of bridges [5]. Amongst these, ground penetrating radar (GPR) [6-8], accelerometers [9], laser scanner [10-11], strain gauges [12], wireless network systems [13], ground-based interferometers [14], global position system (GPS) and levelling [15-16], are applied to transport infrastructures. Nevertheless, on-site sensors can be costly and cannot be installed on all the bridges at the network level, due to economic constraints.

In this context, this paper presents the recent developments in the monitoring and assessment operations of bridges through the application of high-resolution satellite-based remote sensing technologies (i.e. Persistent Scatterer Interferometry (PSI) [17]. and Small BAseline Subset (SBAS)[18]), based on the multi-temporal analysis of SAR satellites images products collected by Synthetic Aperture Radar (SAR) systems. For this purpose, X-Band COSMO SkyMed images provided by the Italian Space Agency (ASI) were acquired and processed in order to detect structural displacements of the Rochester Bridge in Rochester, UK. Outcomes of this investigation outlined the presence of various Persistent Scatterers (PSs) over the inspected bridge, which were proven useful to achieve a more comprehensive monitoring methodology and to assess the structural integrity of the bridge

2. METHODOLOGY

2.1 InSAR for bridge monitoring and assessment

The proposed health monitoring methodology for the assessment of bridges and viaducts is based on satellite remote sensing (multi-temporal Interferometric Synthetic Aperture Radar (InSAR)) technologies involving the processing of different SAR images acquired by X-band operating radar sensors. This allows to better understand the behaviour of the bridges and to identify potential deformations connected to the structural elements of the bridge, such as arcs or stacks. This is possible due to the high ground-resolution available at the ground. This information is extremely useful for bridge and transport infrastructure administrations in order to plan a more comprehensive monitoring process and, consequently, to increase the efficiency of on-site inspections and maintenance activities. Furthermore, it is worthy to note that bridges overpassing rivers may be subject to severe displacements and deterioration caused by the seasonal variations of the water table and its interaction with the foundation soil and the bridge structure (i.e. undermining the bridge piers).
The proposed interpretation phase of the results is achieved by a cluster division of the PS located in the correspondence of the elements of the bridge (i.e. stack and Archs). It is clear that this cluster operation is possible and achieve affordable outcomes only considering the PS deriving from the PSI processing of the high-resolution SAR imagery (i.e. X-Band COSMO-Skymed), such as the ground resolution of the pixel (3m x 3m) and the millimetric accuracy, allow the allocation of the identified PSs to the elements of the inspected bridge.This research paves the way for the application of the InSAR technique to this particular types of engineering problems.

2.2 Multi -temporal InSAR technique

The Persistent Scatterer Interferometry is a multi -temporal InSAR remote sensing technique based on a statistical analysis of SAR images, which is able to identify long-term high phase stability pixels of coherent point targets, namely Persistent Scatterer (PS) [17-19].

This approach allows to estimate the displacements occurred between different acquisitions by a separation between the phase shift related to the ground motions and the phase component due to the atmosphere, the topography and the signal noise contributions [19-21].

An advantage of these techniques is the relatively light data-processing required for the assessment of displacements and the detection of critical areas, as opposed to a higher computational load generally needed by the use of other approaches [22-23]. To this effect, the multi-temporal InSAR approach has proven ideal in monitoring transport infrastructures, as the high density of radar stable targets allow for more accurate measurements.

In the last few years, several multi-temporal InSAR techniques were developed, such as the PS-InSAR [19-20], SBAS [18, 21], and SqueeSAR [23] techniques, for the detection of PS point targets based on different pixel selection criteria (i.e. amplitude dispersion index or coherence). To this effect, several research related to the application of the PS-InSAR techniques for the monitoring of transport infrastructures such as railways [24-29], highways and tunnels, [30-32], bridges [33-36] and airport runways [37-38] can be found in the literature. This evidence confirms a wider use of the satellite-based remote sensing techniques to these specific areas of application, as a popular infrastructure asset management strategy tool.

However, SAR satellites can only detect displacements in the Line-of-Sight (LoS), with reference to the specific orbit related incident angle. Therefore, the displacement detected is a component of the real displacement occurred on the ground. Different methods have been proposed in the literature to overcame these occurrences and evaluate the real displacements-velocity-vector and their components. This is performed by integrating the information of the PS related to the same structure, if a dataset acquired in different acquisition geometries (i.e. Ascending and Descending) is available. [39-41].

3. EXPERIMENTAL FRAMEWORK

3.1 The case study: The Rochester Bridge

The Rochester Bridge is composed by four different bridge decks, built at different time stages (Fig. 1). In the late fourteenth century, the old Roman bridge was destroyed by a winter storm. The medieval bridge constructed in its place had eleven stone arches and a drawbridge. A consistent deposit of silt in the riverbed led to the alteration of the medieval bridge in the 1820s when a large central arch was provided and, in the 1850s, to the construction of a new cast iron Victorian bridge with three arches and a swing bridge.
The nineteenth-century bridge was reconstructed between 1910 and 1914, and arches were installed at their present position above the roadway, to provide more clearance for ships movement under the bridge. Between 1965 and 1970, the Rochester Bridge Trust built a second roadway bridge on the piers of the disused railway bridge immediately downstream from the roadway bridge. The reconstructed Victorian bridge is nowadays known as the “Old Bridge”, whereas the second roadway bridge is known as the “New Bridge” [42].

Fig. 1. Main features of the Rochester Bridge, UK

3.2 ASI’s COSMO-SkyMed Mission: overview and status

COSMO-SkyMed (Constellation of Small Satellites for Mediterranean basin Observation) is a constellation of four equal spacecrafts equipped with SAR operating in X-Band (9.6 GHz) andwith Payload Data Handling and Transmission (PDHT) for the on-board storage and downlink of the SAR data. The COSMO-SkyMed system operates with a wavelength of 3.1 cm and three different sensor modes with different resolutions for a wide variety of applications. The most exploited sensor mode is the STRIPMAP medium resolution mode, with a 3 m ground-resolution cell which allows, under ideal conditions, a millimetre accuracy of the measurements [43].

The system was conceived and funded by ASI and the Italian Ministry of Defense (MoD) which manage the program in cooperation, and it was entirely developed and produced in Italy by Thales Alenia Space Italy (TAS-I) as the Prime Contractor, with the support of Telespazio for the Ground Segment and logistic and operations and Selex Galileo [43]. A general description of the COSMO-SkyMed system architecture is given in [43-45].

The first generation four satellites of the COSMO-SkyMed constellation were launched in the time range 2007-2010, and, currently, all of them completed their nominal operational life (5.25 years), but the constellation is still operating and provides images with the required image quality. The second-generation (CSG) consists of two additional satellites joining those of the first generation. They will provide the users with new acquisition modes, improved performances, new operative solutions and enhanced capability to manage and satisfy heterogeneous and complementary dual use (i.e. Civilian and Defense) requirements, thus ensuring the continuity of the SAR operations. The first satellite of the second generation (CSG-1) was launched from Kourou on 18 December 2019 by Arianespace using a Soyuz rocket.

3.2.1 COSMO-Skymed SAR datasets

In this study, a high-resolution X-Band SAR dataset was collected and processed by the PSI technique to assess potential displacements on the Rochester Bridge.

The assessment of the area is carried out by processing higher resolution X-Band SAR data collected by the COSMO-SkyMed mission (COSMO-SkyMed Product - ©ASI: Italian Space Agency, 2017-2019, All Rights Reserved) delivered under the license to use. These products were provided by ASI in the framework of the Project "MoTIB: Monitoring Transport Infrastructures and Bridges, ID 742, (COSMO -SkyMed© Open Call for Science)", and distributed by the e-Geos group. It is worth to mention that the COSMO -SkyMed archive relies on a single acquisition geometry, therefore at this stage of the research we will refer to the displacements detected in the LoS of the satellite.

Tab.1 – Main features of the COSMO-Skymed mission - ASI (Italian Space Agency)

COSMO-SkyMed (ASI: Italian Space Agency)	
Number of Products	39
Product Type	Stripmap Himage
Acquisition geometry	Descending geometry
Reference Period	03/ 2017–12/2019
Frequency / Wavelenght	9.6 GHz / λ =3.1 cm
Range Resolution-	3m
Azimuth Resolution	3m

To this effect, a PSI analysis was developed to monitor and detect structural displacements of the bridge and achieve useful information for integration with on-site inspections on the bridge in future analyses. It is fair to remind that in the monitoring of critical structures, such as bridges, the accuracy of the measurements is a key factor to identify critical movements and achieve a more accurate interpretation of the results.
However, the provision of high-resolution archive datasets must be regarded as a unique historical source of information that cannot be collected with any other available on-site equipment. Therefore, the analysis of these outcomes is fundamental for the development of future analyses and new algorithms for the assessment of transport infrastructures.

3.3 PSI Processing

The PSI data have been processed following the Persistent Scatterer Interferometry (PSI) [17, 20] approach, by means of the Interferometric Stacking Module of the Software SARscape [46] integrated in the Software Envi. The software is licensed within the framework of the project MoBI: "Monitoring Bridges and Infrastructures Networks" (EOhops proposal ID 52479), approved by the European Space Agency (ESA).

More specifically, the PSI technique operates by the application of the following stages [17,19,20]:

i. a statistical analysis of the amplitudes of the electromagnetic (EM) returns is made on a pixel-by-pixel base to compute the Amplitude Dispersion Index (D_a), reported in Eq.2, where μ and σ are the mean and the standard deviation of the amplitude values, respectively. This index is a measure of the phase stability over time for each pixel at least for high Signal-to-Noise Ratio (SNR) values.

$$D_a = \sigma / \mu \tag{1}$$

ii. Identification of Persistent Scatterer Candidates (PSCs) by computing the dispersion index of the amplitude values relative to each pixel. These are pixels with a value of stability index that exceeds a fixed threshold, typically 0.25;
iii. computation of the interferometric phase $\Delta\phi_i$ for any PSC, at any i^{th} interferogram;
iv. removal of the atmospheric phase contributions, orbital and noise-related effects from the interferometric phase and identification of the phase shift due to displacements only.

As a result of the above process, stable reflectors, i.e. the PSs, can be identified over the inspected area.
At the end of the process, displacement evolution trends can be generated for each PS, to provide an overview of the average ground motion over the entire area of interest.

4. RESULTS

Several PSs obtained by the processing of COSMO -SkyMed X-Band products were identified on the Rochester Bridge. It was noticed that a number of PSs presented consistent deformation trends linked with a down-lifting occurrence, with a seasonal deformation trend most likely related to the flow peak of the river Medway.

The set of PSs resulting from the processing of the COSMO -SkyMed in descending geometry data is shown in Fig.2 and Fig.3.

Fig. 2: PSI results identified on the investigated area displayed in relation to the average trend of velocity (green points are stable scatterers). (Copyright: "COSMO-SkyMed Product – ©ASI – Italian Space Agency –2017- 2019. All rights reserved")

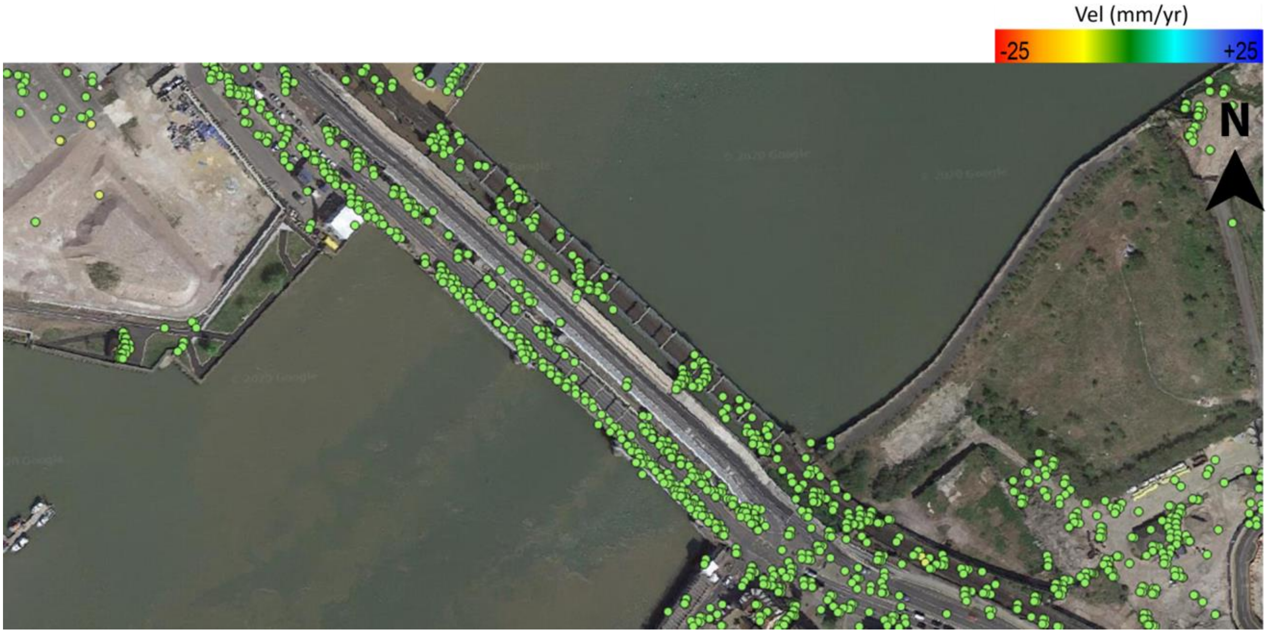
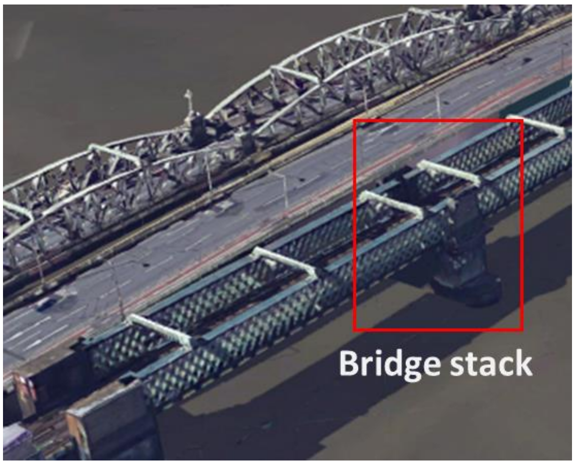


Fig. 3: detailed PSI results obtained from the processing of the COSMO-SkyMed products – ©ASI – Italian Space Agency (Copyright: "COSMO-SkyMed Product – ©ASI – Italian Space Agency –2017- 2019. All rights reserved")

The processing of the X-Band COSMO-SkyMed products allow to detect a large amount of PS point targets over the entire bridge, as expected. This is clearly shown in Fig.2 and Fig.3, where the identified PSs, exported in a GIS platform and displayed by the average velocity motion, are located over the investigated bridge. To this effect, no critical areas were identified in reference to the velocity value of the motion. Velocity values of deformation of the stable scatterers are around +1.20 mm/yr and -1.31 mm/yr.

The interpretation phase of the multiple and randomly distributed outcomes proposed in this paper is achieved by a cluster division of the PSs located on the stack and at one of the arches of the Bridge. To this effect, it is worthy to mention that this cluster operation makes sense and it can provide representative outcomes only considering the PSs from the PSI processing of the high-resolution SAR imagery (i.e. COSMO-SkyMed). This involves a ground resolution of the pixel (3m × 3m) and a millimetre accuracy for the correct allocation of the PSs to the corresponding structural elements of the bridge.

a) 

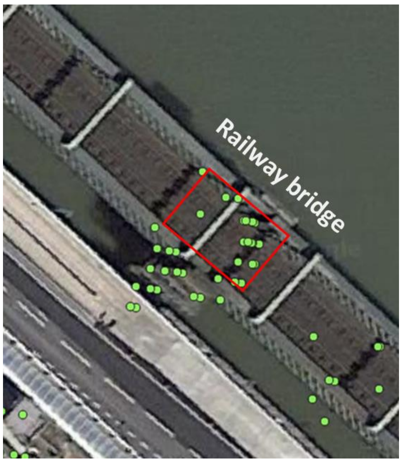
b) 

Fig. 4: Interpretation phase of the PSI technique results: a) selection and b) potential correlation of the cluster of PS points associated to structural elements of the bridge (arch)

For the selected PS reported in Fig. 4b, an analysis of the average velocity motion and the historical time-series was developed over a three-years time period (January 2017 to December 2019).

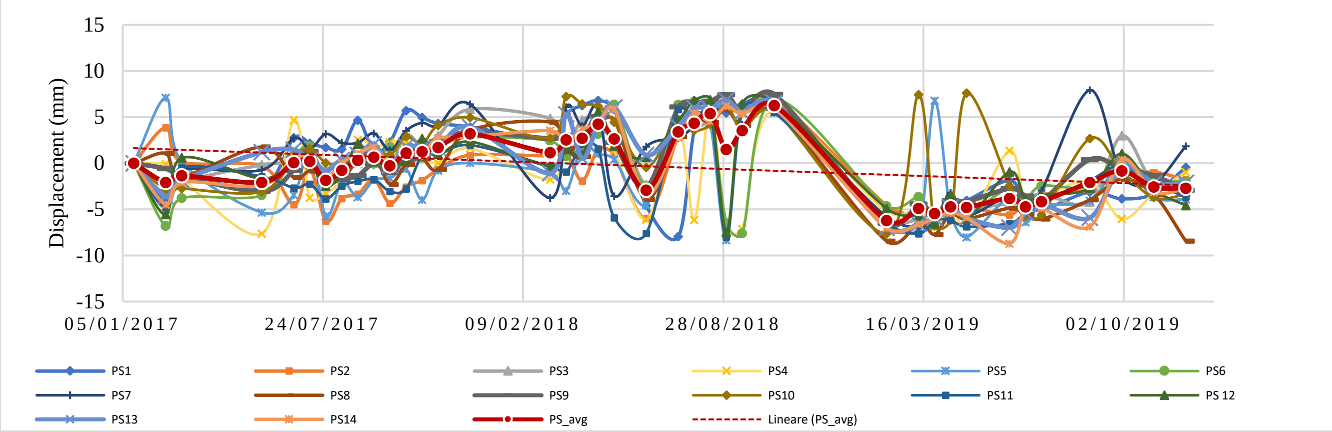


Fig. 5. PS located on the stack of the "railway bridge": reconstruction of a single time-series and deformation velocity starting from the PS sample.

By observing the results reported in Fig. 5, no critical areas or significant subsidence phenomenon are highlighted for the identified PS cluster. On the other hand, an average down-lifting deformation trend of a scale of -5 mm in the three years under analysis was observed on the selected element. This could be likely related to the interaction between the river and the bridge piers. It is fair to observe that, in order to investigate potential sources of displacement related to the railway bridge superstructure, and evaluate the actual subsurface conditions of the bridge-deck foundation, on-site inspections are necessary. For this purpose, the analysis of the PS results can be regarded as an effective management tool for the planning of on-site inspections with ground-based non-destructive testing techniques (e.g., multi-frequency GPR investigations).

Furthermore, seasonal variations were identified across the entire fourteen PS points for the cluster associated to pier n.2 (from South-North direction), of the "railway bridge", with a temporal coherence threshold of 0.75. This analysis paves the way for future investigations about a potential correlation between the observed displacements and the hydrometric data. Under these circumstances, it is worth to mention that the flow-peak of the river Medway can cause the movement of the stack of the bridge. This could be take into account for further examination, to better understand the seasonal trend of the bridge structure, characterised by consecutive up-lifting and down-lifting displacements, outlined in the historical time-series of the identified PS. This evidence could be taken into account for future on-site inspections by verifying the internal state of the bridge deck with ground-based NDT methods, such as GPR and the ground-based interferometer.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

This research demonstrates the capability of the Persistent Scatterers Interferometry (PSI) remote-sensing technique to be used as an innovative monitoring methodology for the monitoring of bridges, by means of the PSI remote sensing satellite-based approach. For this purpose, X-Band COSMO-SkyMed products provided by the Italian Space Agency (ASI) were acquired and processed in this study. Furthermore, a PSI analysis was developed to monitor the structural deformations of the Rochester Bridge in Rochester, UK, a bridge of historical value.

With reference to the methodology discussed above, the presented multi-temporal Interferometric Synthetic Aperture Radar (InSAR) technique was effective at detecting potential areas subject to an evolving subsidence and down-lifting displacements over the investigated area. In turn, the analysis of the high-resolution X-Band COSMO-SkyMed products allowed to provide transport infrastructure managers and administrators with valuable information for prioritising maintenance interventions and preventing catastrophic events.

Results of this investigation outlined the presence of numerous Persistent Scatterers (PSs) over the inspected bridge, which were proven useful to achieve a more comprehensive health monitoring and assessment of the structural integrity of the

bridge. The paper contributes to proving that the satellite remote sensing interferometric analysis is a insightful technique for monitoring deformations in historic masonry bridges and, at a broader extent, in transport infrastructures exposed to natural hazards.
As a future development of the present research, it is proposed to directly acquire the data in the two acquisition geometries to correct and calculate the real components of the displacement. It should be also considered that differential displacements of the bridge piers can affect its structural stability if they reach a certain threshold. These alerts become more critical as a function of the type of bridge and the functionality (i.e. high values of displacements can cause catastrophic events such as train derailments).

This research paves the way for the development of a novel interpretation approach relying on the integration between satellite remote-sensing data and non-destructive information collected on-site (e.g., GPR surveys, GB-SAR and the laser scanner), to optimise and improve the efficiency of the current maintenance processes of transport assets.

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The COSMO-SkyMed Products® - ©ASI: Italian Space Agency, 2017-2019, All Rights Reserved- are © of the ASI (Italian Space Agency), delivered under the license to use, in the framework of the Project "MoTIB, ID 742" accepted by ASI. The license for using the software ENVI SARscape ® is granted by the ESA (European Space Agency) approved project "MoBI: Monitoring Bridges and Infrastructure Networks", EOhops proposal ID 52479. In addition, the Authors would like to acknowledge and thank the Rochester Bridge Trust for facilitating and supporting this research.

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