Integration of PSInSAR, BIM and GIS 3D for Infrastructure Monitoring

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Abstract

Land subsidence and uplift can affect extensive areas and pose a threat to the stability of existing infrastructure. Large-scale monitoring of deformation phenomena is essential for the early detection of anomalies and sudden changes in land geomorphology. Within this framework, numerous studies in the literature are concentrating on the application of SAR data to monitor and evaluate these phenomena, highlighting the need to integrate this type of data with three-dimensional representations of the examined territory. The aim of this research is to integrate deformation data with advanced technologies common in the structural field, such as Building Information Modelling (BIM), and geospatial data management tools, such as Geographic Information Systems (GIS). Using data from Sentinel-1A and Sentinel-1B, processed through StaMPS-MTI and subsequently integrated into an interactive Cesium-based environment, it was possible to associate each BIM component with a deformation-related risk, calculated with PSInSAR technique. This association enabled the identification of the most vulnerable components of the structure and, for the case study, revealed a slight subsidence trend near one of the structure's foundations. The results highlight the strong potential of this integration, offering a valuable tool for more in-depth and advanced analyses in an intuitive and interactive way.

1. Introduction

Italy is characterized by a very extensive infrastructure network that includes railways, roads and highways, airports, ports, and water infrastructure. Transport is one of the main sectors of the country, with roads being the primary mode of transport, especially in rural and suburban areas, which make up much of the Italian territory. In recent decades, most infrastructure investments have been earmarked for roads, while ports, airports, and railways are the sectors that have shown greater resilience. The need to monitor infrastructure arises mainly from its tendency to deteriorate. Corrosion and aging of materials cause structural weakening, increasing the risk of damage and failure. At the same time, wear and tear from heavy vehicle traffic creates continuous pressure on roads and bridges, damaging materials and compromising structural stability, with the risk of failure and vulnerability to stress. Added to this, the scarcity of resources allocated to maintenance is another critical factor. From the global financial crisis to the pandemic, Italian spending on infrastructure monitoring and maintenance has decreased, posing a risk to transport safety.

To address these issues, several advanced and integrated monitoring systems allow for precise measurements. These systems include, for example, structural sensors such as accelerometers (Bono et al., 2025), deformation sensors (Cheng et al., 2025), thermal imaging cameras (Gu et al, 2024), and vibration sensors, which enable the analysis of the health status of bridges, in particular of the deck, superstructure and substructure.

In this context, ANAS Gruppo FS Italiane (Anas, 2025), which has the task of monitoring the road network of competence in Italy, in order to analyze the structural conditions of the parts that make up the infrastructure and to define the maintenance activities of the interventions, costs and associated times, has decided to adopt a monitoring platform for bridges and viaducts by installing local detection systems on the bridges, applying parameter analysis algorithms and connecting the collected data to a centralized system that allows control and management at a national level. With this plan called the SHM (Structural Health Monitoring) Program, 1,000 bridges and viaducts are monitored with sensors. This choice was made through a selection of existing structures according to certain criteria:

- Structures belonging to the SNIT NETWORK of level 1 and TEN on type A and B roads (motorway and main extra-urban road) and some of type C.
- Span greater than 20 m.
- Structure status index that includes medium, medium-high and high anomaly.
- Structures mainly with pre-stressed reinforced concrete decks.
- Structures in operation for over 50 years.

This program, of census, classification and management of risks and dynamic monitoring of infrastructures has the aim of virtualizing the structures also through the creation of BIM information models and the use of Artificial Intelligence algorithms for the definition of predictive maintenance processes.

The monitoring process through sensors is certainly an accurate and detailed process but must face two substantial problems: the enormous quantity of data detected by the sensors and the need to focus only on some bridges, not being able to consider the entire network of existing infrastructures, and on a large scale through rapid and low-cost measurements, considering that the total number of bridges and viaducts in Italy is approximately 14,000 (Serlenga et al., 2021).

For this reason, less expensive bridge monitoring techniques are being evaluated that can also be carried out by regional and local bodies in order to support the work at a national level that is being carried out to date. A low-cost and versatile system is represented by drones (Aela et al, 2024), which can inspect bridges, tunnels, and difficult-to-reach structures. These tools provide high-precision results using high-resolution cameras and Structure from Motion techniques.

Among these, a technology that is gaining increasing attention in literature and is used for monitoring structures, particularly to detect deformations, subsidence, and failures of the terrain on which these constructions rest, is Interferometric Synthetic Aperture Radar (InSAR) technology (Angiulli et al., 2005), (Kakoullis et al., 2024). This remote sensing technique allows for the analysis of large areas with high precision, reaching accuracy at the millimeter level, and provides useful information on both slow and fast movements related to the ground, enabling early intervention in the event of irreparable structural damage.

An example of the use of InSAR in infrastructure monitoring is the study by Piter et al. (Piter et al., 2024), in which the authors evaluate the effectiveness of various pixel selection methods for monitoring displacements in transport infrastructures using Sentinel-1 data. Another example is the study by Kim et al. (Kim et al., 2024), in which satellite SAR data were used to monitor the impact of buildings on the ground, also improving infrastructure maintenance practices in Korea.

The potential of the method dates back to before the launch of the Copernicus Sentinel satellite constellation and the importance of radar data in identifying areas that warn of structural disasters is already demonstrated by a study by Sousa et Bastos in 2012 (Sousa et Bastos, 2012) in which a multi-temporal analysis (MTI) was conducted through 57 ERS-1/2 scenes that allowed to establish that the tragic event of the collapse of a bridge that occurred in Portugal was linked to the movement and extraction of sand adjacent to the foundations of the bridge. The underlying ground had already shown signs of subsidence with movements of 20 mm/year, highlighting that the use of such satellite data can evidently favor the identification of important anomalies.

At the same time, the integration of geospatial data and the spatial location of the structures allows to have a holistic vision of the deformation process that can be influenced by different factors coming from information that can be managed within Geographic Information Systems (GIS). The potential of this technology is consolidated and there are numerous technological advances that can be found in the literature, including for example WebGIS and the new concept of Digital Twins (Barrile et al., 2025), (Scolamiero and Boccardo, 2025), virtual twins of the systems or processes examined that allow obtaining a three-dimensional, active and real-time updated representation of the conditions of the object examined.

In this context, this work intends to present an approach for integrating SAR data with 3D geographic information systems (GIS) to identify risk points in infrastructure that could lead to significant structural problems and to identify particular trends of structural failure in a bridge located in the Province of Reggio Calabria. This spatial and multi-temporal approach is innovative because, in addition to using the Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique to define deformation points at the territorial level, these data are integrated with dynamic 3D models. The BIM model is integrated into the GIS, displaying deformations from a geospatial point of view and the potential structural risks associated with the infrastructure present there.

2. Methodology

The methodology of this work is divided into three phases. The first phase focused on the acquisition of SAR data and the application of the PSInSAR technique to monitor small deformations, using persistent scatterers, i.e., points that reflect the signal in a stable manner. The Point Scatterers (PSs) are assigned to the corresponding roads through geoprocessing tools. The second phase focused on the creation of 3D models of the infrastructure, using digital terrain models and BIM (Building Information Modelling) of the infrastructure to obtain the 3D model of the infrastructure to be monitored. Finally, in the third phase, the deformations calculated with the PSInSAR technique are integrated with the 3D GIS data, where each point is associated with the 3D geometry of the infrastructure, allowing for detailed visualization of where the displacements occur. This analysis allows for the prediction of future issues and the identification of potential structural risks or significant damage that could occur in the structure from a 3D point of view, allowing for important structural considerations. For this purpose, Sentinel-1 SAR satellite images from the Copernicus Earth Observation program were used (Potin et al., 2019), (Geudtner et al., 2021) along with the PSInSAR technique for deformation data and a 3D BIM model of the infrastructure. Figure 1 illustrates the entire methodology.

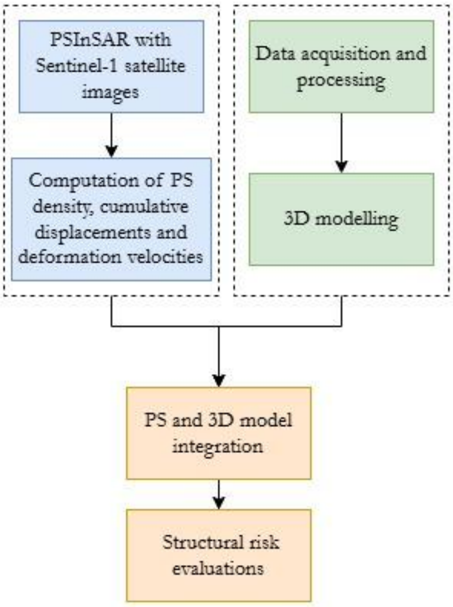

Figure 1. Proposed methodology.

From the acquisition and processing phase with the PSInSAR technique, images from 2019 to 2023 were analyzed in a study area in southern Italy (Barrile and Bilotta, 2008). The Sentinel-1A and Sentinel-1B satellite imagery dataset, with a spatial resolution of 5x20 m (range x azimuth) and a revisit time of approximately 6 days, were selected with both ascending and descending orbits and of the Single Look Complex type with Interferometric Wide swath (IW) acquisition mode. The choice to use both possible orbits was made to obtain bidirectional coverage and therefore calculate both vertical and horizontal deformations (since the estimated deformations refer to the satellite Line of Sight (LOS)). A dataset of Sentinel-1A and 1B scenes was processed, creating a series of interferograms. The satellite images used come from a constellation of satellites to which Sentinel-1C has been added in 2024 (Jans et al., 2025). This latest satellite launched into orbit works in C band like its twin Sentinels and is equipped with a dual-polarized radar system that allows different polarization modes. Like Sentinel-1A and 1-B, Sentinel-1C data are free and open through the dedicated Copernicus portal. This data was not used for this study, but further analyses in the context of territorial deformations with this new satellite are being studied by the authors.

The technique used for the determination of the PSs is StaMPS-MTI, or the Stanford Method for Persistent Scatterers-Multi-Temporal InSAR (Hooper et al., 2010), which allows to identify the temporal stability of radar targets from the interferometric component of the phase of a radar image. The coherence threshold value was chosen greater than 0.4 and the PSs selection criterion was performed considering the phase and amplitude stability and through temporal dispersion analysis of the radar intensity (with amplitude dispersion < 0.25).

Once the PSs were obtained, the process of which is widely described in Hooper (2008), Hooper et al. (2004), the PSs were initially imported into a GIS system. In order to select and evaluate the PSs falling within the representative sections of the road infrastructure, a mask was created that follows the trend of the road network of the city of Reggio Calabria. A buffer was created, and this buffer was subsequently divided into smaller portions (500 m long) to estimate the density of PSs present in the considered section. Figure 2 shows the process in a GIS environment of selecting the PSs that fell within the created buffer and are representative of the road network. Already from a first visualization of the deformation data that occurred in the years from 2019 to 2023 it is evident that some areas of the metropolitan city adjacent to the city center are affected by deformation phenomena that are around 6.7 mm/year:

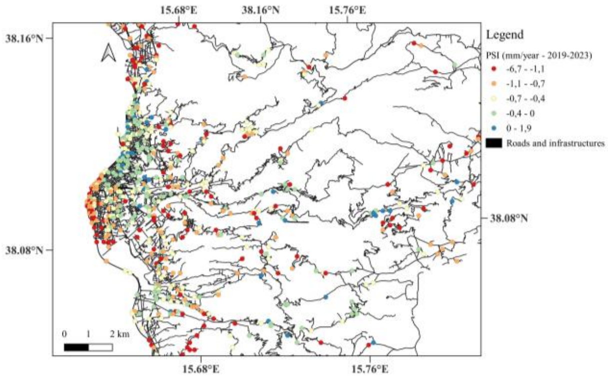

Figure 2. Mean Velocity, PS. 2D map representation of PS.

Figure 3 instead shows the spatial distribution of the deformation velocity in the Reggio Calabria area, where the calculated average velocity was plotted in Matlab as a function of the spatial coordinates of the selected study area. From here too it can be seen that there are several deformation phenomena present in the area, characterized by subsidence rather than uplift. Furthermore, it is possible to notice how the deformations are uniform except for some spots on the coast and others in the hilly area of the study area. In fact, there are several distinct blue points with deformations close to 20-25 mm/year which must necessarily arouse interest due to their location and spatial distribution, concentrated in the area corresponding to the historic city center.

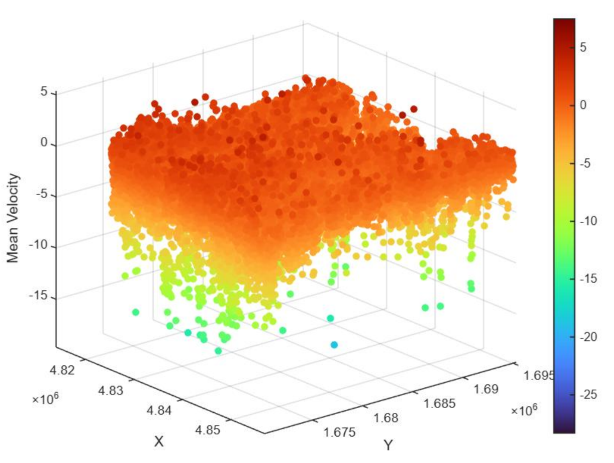

Figure 3. Mean Velocity, PS. 3D map representation of PS.

This work aims to focus on a very busy stretch of road in the city of Reggio Calabria, namely the Strada Statale 106. This road, which connects to the A2 motorway that links Calabria to the rest of Italy, is the artery of the city and thousands of people travel along this road every day. This road passes over several bridges and viaducts, including the Annunziata Viaduct (38.123295 N, 15.663884 E) to the south of the city, adjacent to the Mediterranean University of Reggio Calabria. The infrastructure, managed by a public-private company, ANAS S.p.A, is located in the south of Italy and for this reason exposed to high seismic risk according to Italian INGV (National Institute of Geophysics and Volcanology). The strategic position makes this viaduct fundamental for the entire highway, linking north and south part of the city, allowing circulation of vehicles and trucks outside the city. In case of collapse the entire highway will be interrupted with high risk and consequence on vehicle circulation and emergency response. The viaduct, designed on 1970 and constructed from 1968 and 1980 upon the “Annunziata” river, is a simply supported, beam viaduct made of pre-stressed reinforced concrete with 9 short-spans of 27 m, and a total length of 254 m (in curves). Curvature radius is 150 m, and the medium height of the bridge is 25 m a.g.l. The viaduct was chosen for its simple structure and characteristics. The viaduct deck is composed of a standard module of 29 m with 4 beams and 3 crosses in pre-stressed reinforced concrete. The two decks (one for each direction) are supported by a couple of piers with a common foundation. Piers are made of a rectangular section of 2.50 m x 1.60 m and pier cap dimensions are 8 m x 3 m. Figure 5 shows the mentioned viaduct:

Figure 4. Case study: ‘Annunziata’ Bridge.

At this stage, it was therefore necessary to create a BIM model of the structure under examination (Parekh and Trabucoo, 2024) starting from the point cloud created from a photogrammetric flight conducted by a drone.

The BIM model was created using the ArchiCAD software and allowed us to faithfully represent the actual state of the infrastructure under examination. In this context, BIM has a fundamental aspect as it enables to make important structural assessments and design predictive maintenance interventions. It is therefore vitally important to associate the typical structural information of BIM with assessments related to the transformations that bind the ground on which it rests in order to make assessments based on the available geospatial data. The level of detail (LOD) chosen was 300 (in accordance with AIA standards) and for the purposes of this research work, beams, deck, piers, supports, abutments and foundations were modelled.

Finally, the procedure was created to import the created BIM within a WebGIS (under construction by the authors (Barrile et

al., 2023)) and to create a code for the attribution of the deformation data deriving from the SAR analysis in the imported BIM into the geospatial system, in order to set up an alarm system that identifies the danger associated with the deformation of the ground through different colors. The deformation data are attributed to the BIM model through an associative rule in order to map the deformation on the surface of the BIM model and therefore determine which part of the model is at "risk".
Through spatial matching, the calculated PSs are associated with the closest BIM component within a certain spatial threshold; if multiple components are close together, weighting based on Euclidean distance is applied.
For the semantic visualization, a threshold was set below which no significant deformations occur. Where the components of the BIM model are perfectly aligned with the geospatial coordinates of the deformation data, the distance between the deformation (a geospatial point) and the center of each component was calculated.
To this end, the .gltf model and the GeoJSON of the deformation data on Cesium were imported (Cesium, 2025), through a suitable Python script, attributing the PS values to the three-dimensional model by association with the geographic coordinates. The .gltf model was obtained using Blender and glTF Exporter with simplified geometry to improve web performance. As for the interactive visualization in Cesium, Geoserver was used for the publication of the WMS and WFS layers and PostgreSQL/PostGIS for the storage and management of the geospatial data used.

3. Results

The integration between 3D data and deformation data deriving from InSAR techniques allows to obtain a clear and interactive vision of the points of the ground on which the infrastructure rests that show a tendency to deformation processes. Through GIS analysis techniques, it is possible to identify areas of an infrastructure that are subject to stresses that can lead to possible failures (Figure 5).

Figure 5. First results in terms of identification of areas at risk of deformation resulting from the proposed methodology.

The representation of BIM components through geometric models has allowed for the attribution of PS to individual components, enriching the information related to the BIM elements. This approach enables the analysis of deformation effects over time: the integration of GIS with BIM, and possibly with simulation software, allows for the evaluation of the effects of different movement speeds or structural anomalies, as well as assessing the infrastructure's response to adapt or react to these variations. The result of this integration has enabled the creation of 3D deformation maps, where each structural component of the BIM model changes color based on the amount of deformation it has undergone.
Figures 6 and 7 instead show the BIM model of the Annunziata bridge with all its constituent elements.

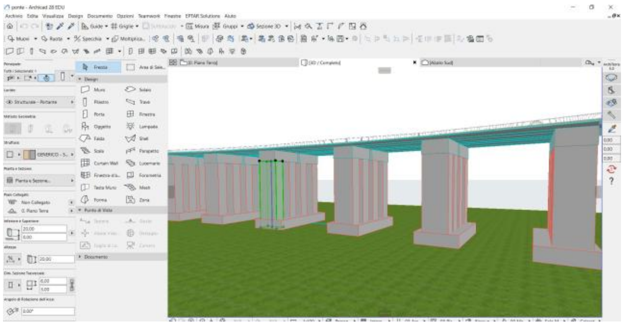

Figure 6. BIM reconstruction from photogrammetric drone survey.

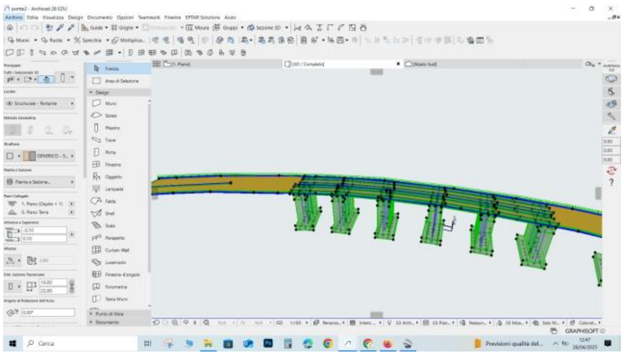

Figure 7. BIM model highlighting the different structural components.

Figure 8 shows the PSs located inside the 3D model of the study area being analyzed. It is clear how the integration between 3D modeling and GIS allows a broader view of the problem: built on the 'Annunziata' river, the ground on which the infrastructure rests could be subject to significant deformations due to the natural path of the watercourse. Several PSs are positioned inside this trajectory, highlighting that the area can cause structural failures to the bridge foundations. In Figure 8 the PSs are represented by yellow dots, in the top right a graphical interface shows the mean velocity deformation value (vertical component) associated with the represented point (0.40 mm) which highlights a phenomenon of slight subsidence.

Figure 8. PSs visualized in a WebGIS environment and integrated together with the three-dimensional model representation of the 'Annunziata' Bridge near the Mediterranea University of Reggio Calabria (Italy).

In relation to the same point at the bridge foundation, it was possible to calculate an RMSE of 0.70 which indicates a good stability of the data around the average value of 0.40 mm as shown in Figure 9.

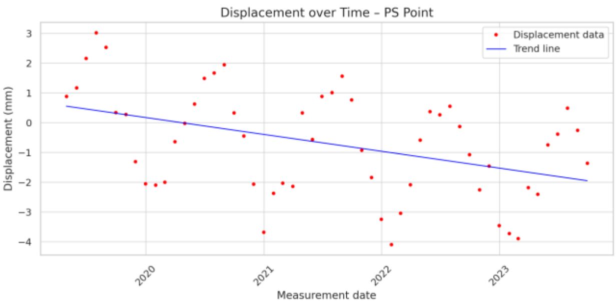

Figure 9. Displacement over Time – Ps Points.

4. Conclusion

Infrastructure monitoring is a research field where many steps forward can be made to improve both inspections and maintenance interventions. This research work fits into this framework with the aim of providing an innovative method to integrate advanced Remote Sensing techniques with three-dimensional and georeferenced representations typical of GIS models. The use of satellite images guarantees wide spatial coverage, allowing for advanced studies on a large scale and for analyzing the possible causes of a deformation process or the effect that this has on the infrastructure, also taking into account the boundary conditions that affect the structure. This work uses the Sentinel-1 satellite images of the Copernicus Earth Observation program, since they are free, open and manageable through the appropriate platform, but there are several constellations and satellites able to provide more detailed information in terms of spatial resolution and review. The latter, however, have the disadvantage of high cost and not constantly covering the areas of interest. Radar satellite images that can be used for these purposes are, for example, those of TerraSAR-X and CosmoSkyMed. As for GIS, Digital Twins are now revolutionizing the model of geospatial information. As faithful virtual replicas, they provide an accurate mirror view of reality and enable advanced predictive assessments, which is an innovative aspect that the authors will focus on in their research concerning model simulations. In fact, studies are being conducted to visualize deformation over time by animating the model. This involves either moving the BIM model or deforming its surfaces to simulate the ongoing effects of the deformation. At the same time, artificial intelligence models are being created aimed at predicting the trend of deformations over time and, therefore, allowing future assessments relating to predictive maintenance interventions. In this area, Machine Learning and Deep Learning can make a significant contribution. The most suitable models for this type of task appear to be Convolutional Neural Networks, which can yield accurate results after being trained on substantial time series data. The development of a Digital Twin platform of the Italian road infrastructure, through the integration of sensor data, Remote Sensing data, BIM and GIS systems, could allow to create a powerful tool for policy makers, in order to make informed choices based on data.

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