Assessment of Masonry Wall Deformation through Vertical Displacement Gradients Using COSMO-SkyMed SAR Interferometry: The Case Study of Archaeological Park of Pompeii

Francesco Aufiero[1], Vincenzo Calvanese[2], Alessandro Di Benedetto[1], Margherita Fiani[1], Luigi Petti[1], Alessandra Zambrano[2], Gabriel Zuchtriegel[2]

[1] Department of Civil Engineering, University of Salerno, Fisciano (SA), Italy
(faufiero, adibenedetto; m.fiani; petti)@unisa.it
[2] Archaeological Park of Pompeii (PAP), Ministry of Culture (MiC), Pompeii (NA), Italy
(vincenzo.calvanese, alessandra.zambrano, gabriel.zuchtriegel)@cultura.gov.it

Keywords: Archaeological Park of Pompeii, PSInSAR^{TM} Technique, Vertical Displacement Gradient, Deformation Monitoring

Abstract

A multi-level, multi-scale monitoring approach, leveraging WebGIS, Internet of Things (IoT), and Digital Twins, has been implemented at the Archaeological Park of Pompeii (PAP) to support proactive maintenance process for the preservation of the site. This study integrates satellite techniques, particularly PSInSAR^{TM}, into the General Assessment (GA) level, significantly enhancing monitoring strategies. Data from the COSMO-SkyMed mission, led by the Italian Space Agency (ASI), have been used to accurately map vertical displacements, highlighting areas of subsidence and uplift. A tailored process was developed to determine the primary directions in the horizontal plane of the ancient walls inside the PAP. Vertical displacement velocity gradients were then calculated along these directions by combining the ascending and descending acquisition geometries. The gradient analysis along the principal directions of each insula of the PAP provided a clear representation of deformations, which is crucial for pinpointing problematic areas and directing further in-situ investigations. This approach underscores the effectiveness of PSInSAR^{TM} in both emergency management and routine maintenance, offering valuable insights for the preservation of cultural heritage in Pompeii.

1. Introduction

Safeguarding Pompeii has long been a complex task for those in charge of its conservation, management, and promotion as a UNESCO World Heritage site. Spanning 66 hectares, with just over two-thirds uncovered through excavation, the city embodies an extensive yet delicate archaeological legacy, including buildings, wall paintings, artifacts, mosaics, and infrastructure preserved by the eruption of Vesuvius in AD 79 (Figure 1). Across the centuries, Pompeii has acted as a global reference point for testing innovative methods in excavation, restoration, and heritage preservation. The outcomes of these initiatives, however, have depended not only on technical measures but also on the administrative frameworks chosen for governance. A notable case is the Great Pompeii Project (GPP), carried out between 2012 and 2022. Its achievements are largely linked to the coordinated structure and comprehensive management system adopted, which integrated protection, research, conservation, accessibility, and educational outreach (Osanna, 2020; Picone and Osanna, 2018; Mauro, 2019).

Figure 1. A view of the Archaeological Park of Pompeii.

A "Sustainable Management Model" is a comprehensive, process-based solution for implementing effective management in a complex site such as Pompeii. Sustainability involves a range of disciplines and requires a holistic approach to address multi-dimensional values (Hosagrahar et al., 2016). The challenge for Pompeii is to safeguard and further improve on the high-quality standards achieved by the GPP in terms of conservation, renovation, access, and education through an ordinary and sustainable management process. The proposed model aims to integrate these aspects with economic sustainability and increased self-financing capabilities. It is inspired by the paradigm of "circular archaeology" that rejects a priori hierarchies between various aspects of cultural heritage management such as conservation, research, public outreach, and economic development, underlining their mutual interdependencies (Zuchtriegel, G., 2022; Zuchtriegel, G. et al., 2024).

As outlined in the UNESCO publication on managing cultural heritage (UNESCO, 2013, Managing cultural world heritage), sustainable development entails the responsible application of limited resources that strikes a balance between fundamental human needs and those resources available to future generations.

Regarding cultural heritage, sustainable development can be understood in two ways:

1. Intrinsic: as a concern for maintaining the heritage, considered as an end.
2. Instrumental: as the possible contribution that heritage and its preservation can make to the environmental, social, and economic context.

The first consideration rests on the idea that cultural heritage, together with the capacity to interpret the past through its tangible remains, is essential for strengthening local communities and improving their quality of life. The second highlights that the cultural heritage field must also take responsibility for contributing to global sustainability, especially in light of increasing human impact, limited financial and natural resources, and the challenges posed by climate change. Within this perspective, the EU Framework for Action on Cultural Heritage identifies sustainability as a key element among its five guiding pillars. (Decision EU 2017/864, European Commission: Directorate-General for Education, Youth, Sport and Culture, 2019). The recognition of cultural heritage as positively affecting social, capital, and economic growth, as well as environmental sustainability is well-established.

The five pillars of this Framework for Action are:

1. Cultural heritage for an inclusive Europe: participation and access for all.
2. Cultural heritage for a sustainable Europe: smart solutions for a cohesive and sustainable future.
3. Cultural heritage for a resilient Europe: safeguarding endangered heritage.
4. Cultural heritage for an innovative Europe: mobilising knowledge and research.
5. Cultural heritage for stronger global partnerships: reinforcing international cooperation.

Managing cultural sites can be significantly challenging when hazardous conditions are present (Romao and Bertolin, 2022). One could argue that this observation also applies, at least in part, to the setting of Pompeii. Recent weather events have underlined the vulnerability of the area surrounding the site, making it clear that it remains insufficiently equipped to face the specific hazards it is exposed to characterizing it (Sesana et al., 2021). Any robust approach to site management should integrate an assessment of the risks and vulnerabilities that endanger its long-term preservation within a sustainable perspective. Establishing preventive measures and strategic initiatives aimed at reducing potential damage or disasters allows resources to be directed toward the proactive and efficient protection of cultural heritage.

Recent research examining the consequences of climate change on cultural heritage highlights the relevance of fluctuations in temperature, rainfall, and wind patterns (Sesana et al., 2021). Findings suggest that archaeological remains are highly vulnerable, with impacts such as:

- Increased rainfall and humidity, combined with rising temperatures, may trigger deterioration processes including corrosion, biological growth, deformation, cracking, and the crystallisation of salts that lead to efflorescence and subflorescence;
- Stronger winds, particularly when carrying sand, salt, or pollutants, can accelerate erosion of surfaces, heighten water penetration, compromise structural stability, and even cause collapses;
- Rising temperatures may intensify freeze–thaw cycles and amplify daily thermal variations, enhancing the incidence of thermoclastism and producing greater physical stress on stone and ceramic materials;
- Warmer and more humid conditions could foster environments conducive to mould development and insect infestation, increasing biological decay.

Our proposed sustainable management framework differentiates between gradual effects caused by ordinary weather fluctuations and those resulting from extreme climatic events, both linked to climate change. While regular variations in climate tend to produce a slow yet continuous deterioration, extreme events usually generate immediate and severe damage. Routine monitoring and preventive care can help mitigate the impacts of gradual changes, whereas targeted risk-reduction strategies can lessen the consequences of sudden disasters. Though hazards such as earthquakes, flooding, oil spills, armed conflict, and epidemics cannot be completely averted, their potential effects can be significantly reduced through proper mitigation measures (UNESCO, 2010).

The purpose of this study is to outline the difficulties encountered by the Archaeological Park of Pompeii and the approaches developed in the aftermath of the GPP, highlighting a pioneering system for monitoring and maintenance structured according to global standards (UNI 10144:2006, 2006 and UNI 10224:2007) as part of a wider strategy focused on fostering sustainable development across archaeological sites and the communities connected to their heritage.

Specifically, this study explores the potential of SAR Interferometry in assessing the condition of ancient masonry structures within the archaeological site of Pompeii, as part of the national monitoring project led by the Colosseum Archaeological Park (D.M. 19/2019).

2. Monitoring of the Archaeological Park of Pompeii

2.1 The Pompeii Sustainable Management Model

The Archaeological Park of Pompeii is a local organisation belonging to the Ministry of Culture of Italy. In addition to the site of Pompeii, the Archaeological Park comprises other museums and cultural heritage sites. These include the Antiquarium of Boscoreale, the Castle of Lettere, the Archaeological Park of Longola in Poggiomarino, the archaeological museum at Quisisana in Castellammare di Stabia, the archaeological sites of Oplontis in Torre Annunziata, the villas of Stabiae in Castellamare di Stabia, Villa Regina in Boscoreale, and the Former Royal Bourbon Powder Factory in Scafati.

The Park's sites lie at the foot of Vesuvius and in proximity to the Campi Flegrei region, one of the most hazardous volcanic sites in the world. Although the hazard linked to Vesuvius appears as the major threat to the area around Pompeii, the Campi Flegrei caldera, a complex and resurgent volcano, has experienced intense volcanism with eruptions concentrated in temporal clusters known as epochs and therefore should not be underestimated (Bevilacqua et al., 2022). Both Vesuvius and Campi Flegrei refer to a single deep magma system, which also feeds magma to Ischia. In addition, the ancient city of Pompeii is situated within a widely recognised seismotectonic context (Latorre et al., 2023) that characterises Southern Italy with high to medium seismic activity. Pompeii's local seismic vulnerability has been evaluated (Amato et al., 2022) through an investigation of the repercussions resulting from the powerful earthquake in AD 62/63. Hydrogeological hazards are equally significant, as they affect the stability of existing walls and the preservation of the site.

The site of Pompeii and the complex problems that characterise its conservation and management have long attracted the attention of the international community. Negative media coverage culminated in November 2010 following the collapse of the Schola Armaturarum, which was attributed to a lack of maintenance and the effects of hydrogeological instability - a factor that is being amplified by the effects of climate change.

The Great Pompeii Project was conceived as a response to the preservation problems that the collapse had dramatically highlighted, thanks to the joint action of the then Ministry of Cultural Heritage Activities and Tourism and the Presidency of the Council of Ministers, with the aim of stopping the degradation and improving the conditions of the extant remains.

As part of the project, the Information System (SiPompei) was developed—a digital platform that documents and catalogues the entirety of Pompeii. SiPompei's main goal is to support maintenance operations through a georeferenced relational database for monitoring vulnerable conditions (Mauro, 2019). However, its limited ease of use led to mi nimal adoption by the Archaeological Park personnel, and consequently, the platform was rarely updated.

In recent years, the open-access archive OpenPompeii has been launched to ensure more accessible and user-friendly

https://doi.org/10.5194/isprs-annals-X-M-2-2025-29-2025

availability of research data, images, and digital collections of the Park. OpenPompeii is connected to SiPompei, the Archaeological Information System of the Vesuvian Area (SIAV), and digital photographic and historical archives (Tolomeo). SIAV, created between 2001 and 2007 prior to the GPP, was designed to compile information from the Vesuvian area and provide online access (Miele F., 2011).

Regarding safety and security, a further project named Smart@POMPEI was developed to manage and control the safety of both visitors and archaeological monuments thanks to an agreement signed in May 2015 by the Ministry of Cultural Heritage and Activities and Tourism (MiBACT) and the National Research Council (CNR). Smart@POMPEI led to the development of a platform capable of integrating video surveillance, access control, anti-intrusion systems, and environmental monitoring by means of sensors, drones, etc. Figure 2 describes the map of the Informative Systems of Pompeii.

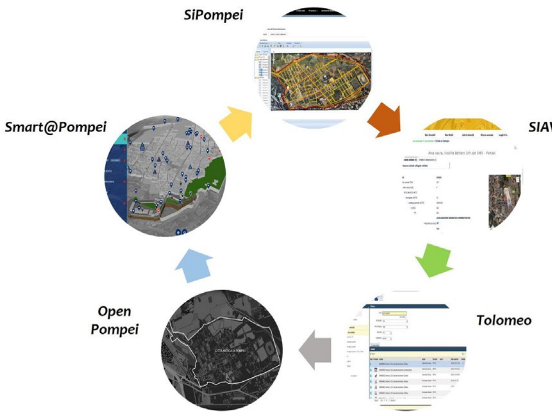

Figure 2. Information Systems for the management of the Archaeological Park of Pompeii.

These information systems are part of the sustainable management operations of an archaeological site. Indeed, this one need many different and useful approaches to conservation, restoration, and rehabilitation. It is essential to recognise the substantial differences between conservation, restoration, and renovation (Petzet M., 2009):

- **Conservation** involves preserving and maintaining the integrity of a monument. Through stabilisation and safeguarding, conservation prevents further deterioration and protects the original material.
- **Restoration** seeks to restore or highlight hidden, damaged, or altered elements of a monument, emphasising its historical and artistic significance. New elements are added only after the original material has been stabilised.
- **Renovation** aims at renewal, striving to achieve visual and aesthetic unity by "making the monument new again."

These methods form a connected hierarchy of preservation measures that can be applied sequentially or simultaneously according to the specific context. Among the activities that ensure the survival of archaeological remains (repair, stabilisation, rehabilitation, and modernisation) maintenance plays a pivotal role. Article 4 of the Venice Charter (Charter, V., 1964) places maintenance at the forefront of site and monument conservation.

After the GPP, an extraordinary initiative funded through special resources, attention must increasingly turn to daily maintenance carried out using ordinary budgets. Effective management must consider all potential risks, including both common threats and extreme events that could escalate into disasters. Accordingly, management strategies should incorporate preventative and mitigative measures, complemented when needed by a disaster risk management plan (UNESCO, 2010).

Integrated management of cultural heritage sites is crucial and can be examined through three perspectives: philosophy, process, and outcomes (UNESCO, 2013).

- **Philosophy** defines the intended organisational transformation, the mindset of stakeholders, and interdisciplinary collaboration to achieve objectives.
- **Process** highlights collaborative and flexible approaches that encourage innovation and creativity within a supportive work environment.
- **Outcomes** consist of improvements and innovative solutions at scientific, technical, and administrative levels, which can be applied to other heritage sites, generating benefits beyond the immediate organisation.

The Sustainable Management Model for Pompeii addresses contemporary challenges such as climate change, sustainable development, and the reinforcement of cultural values. Key innovations include:

- It is considered a "model" rather than a one-off "project", designed to establish a sustainable management framework that continues beyond initial funding and becomes part of routine Park management.
- It focuses on small-scale, integrated actions, which may appear limited individually but collectively form a long-term strategy capable of accommodating evolving requirements, such as environmental and economic changes.
- It was developed from the ground up to cover Pompeii and its surrounding sites, aiming to promote economic growth and development throughout the broader archaeological region.

Pompeii's comprehensive management strategy is structured around four main goals, each linked to key risks and areas for improvement (Figure 3):

1. Protection and maintenance of heritage assets.
2. Sustainable visitor services, educational programs, and communication.
3. Inclusion of local communities and fostering cultural and economic development.
4. Strengthening innovation and leadership capacities across all levels of the organisation.

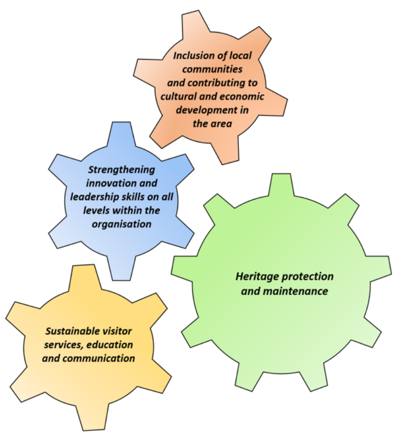

Figure 3. Elements of the Sustainable Management Model of the Archaeological Park of Pompeii.

Within our approach, safeguarding and maintaining the site are central priorities. Maintenance, in particular, plays a vital role in balancing performance optimisation with cost efficiency. It involves technical, managerial, and administrative measures designed to preserve cultural heritage and provide benefits to heritage communities and visitors, both presently and in the long term.
One of the primary challenges for complex archaeological sites is the risk of falling below critical conservation thresholds, as highlighted by the pre-GPP experience. Furthermore, natural threats - including earthquakes, volcanic activity, and the impacts of climate change - must be addressed.
Enhancing safety and managing risks can be achieved on several fronts. Visitor-accessible areas can be expanded and diversified to reduce congestion and anthropic pressure. Examples include new walking routes along the city walls, permanent exhibitions of casts of eruption victims and organic remains in the Great Palestra, temporary exhibition spaces, and accessible storerooms in San Paolino. Development of surrounding archaeological sites and the possibility of evening and nighttime visits also contribute to a richer and less crowded experience, extending visitors' stays. Opening storerooms and excavation zones to guided groups encourages slower tourism and deeper engagement, while ticketing strategies, incentive systems, and free transport to other sites help diversify the overall experience.
Systematic monitoring is indispensable for any model concerned with tangible heritage. Only with comprehensive and regularly updated knowledge of the site can proactive maintenance and effective damage control be implemented. The Archaeological Park of Pompeii has introduced a modern monitoring system, replacing the previous sporadic, ad hoc inspections conducted by archaeologists and architects. Today, digital technologies allow continuous monitoring, periodic updates, and the storage of large datasets for temporal comparisons. AI tools can detect transformation processes, which can then be further analysed by technical staff.
The Sustainable Management Model of Pompeii, represented in Figure 4, emphasises multi- and transdisciplinary approaches and the establishment of a shared language, enabling the integration of diverse expertise and competencies toward a unified vision.

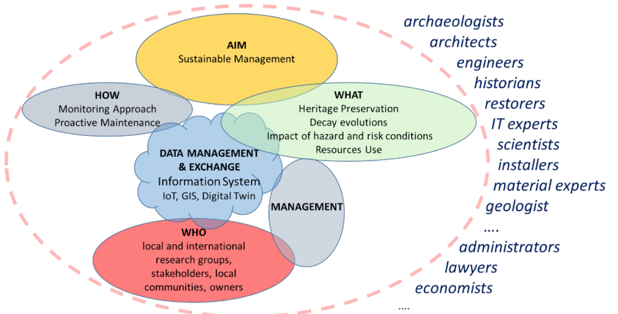

Figure 4. Summary of the Sustainable Management Model for Pompeii.

2.2 The Monitoring Strategy

A successful maintenance approach relies on detailed, current knowledge of how hazards and potential threats develop over time. Preservation initiatives cannot adequately address a complex site like Pompeii without such understanding. Monitoring must therefore be comprehensive, encompassing the full extent of the site, and consistent, with regular inspections providing updated information. Archaeological sites can benefit from methodologies already applied in other fields that employ similar systematic monitoring techniques (Ministry of Infrastructure and Transport, 2020; Pregnolato M., 2019; IM-SAFE, 2020).
Moreover, in the long term, monitoring strategies can only succeed if they are sustainable and not reliant on temporary or special funding (Frangopol and Liu, 2007; Petti et al., 2023; Petti et al., 2024).
Given the complexity and fragility of Pompeii, with its diverse assets and numerous risks, a tailored multi-level and multi-scale monitoring strategy has been established. This system employs various methodologies and techniques, each characterised by specific temporal and data resolutions (multi-scale). Similarly, the precision of assessments is structured across three levels (multi-level):

1. Local Assessment (LA)
2. General Assessment (GA)
3. Detailed Assessment (DA)

The LA provides a broad understanding of the site's condition through annual on-site surveys conducted by multidisciplinary teams, including archaeologists, restorers, architects, and engineers.
The GA generates general overviews via monthly drone flights, with data analysed using artificial intelligence (AI) tools. GA serves as a rapid-response method for emergency management. Both LA and GA help identify and address issues through routine maintenance and determine when a detailed DA is necessary.
The DA is performed selectively based on findings from LA or GA, offering in-depth evaluations. Critical risk factors can also be addressed with the support of monitoring devices.
Pompeii's monitoring system (Figure 5) integrates WebGIS, IoT, and Digital Twins to document the site's condition, enabling the creation of predictive models that guide proactive maintenance strategies.

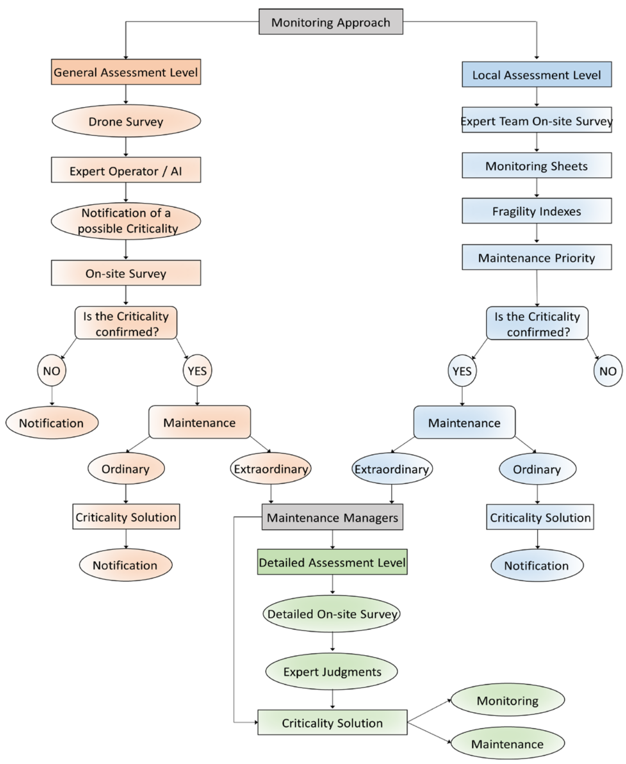

Figure 5. Flow-chart Monitoring approach.

The GA level involves the analysis of high-resolution images, obtained by a drone survey (Figure 6a), with the aim of evaluating the evolution of the site, by comparing images taken in different times of throughout the year. The images are georeferenced using a specific procedure (Figure 6b) and catalogued in the GIS database of the Park.
The LA level involves compiling standardised monitoring forms to identify and describe the most characteristic and frequent forms of decay for each type of element found in Pompeii, such as: wall structures; decorations; architraves; horizontal elements. Figure 7 shows the screenshots of the web app that has been developed to support the periodical surveys.
In the case of exceptional conditions of decay or following exceptional events, the monitoring approach can help evaluate the need for a DA level. The DA level is conducted by teams of experts in the field of archaeology, architecture, engineering, restoration, etc. and includes the use of sensors to improve our understanding of the local conditions. Figure 8 shows an example of a test site in the Archaeological Park of Pompeii.

Figure 6. Survey plan for the acquisition of orthophotos of the Park via drone

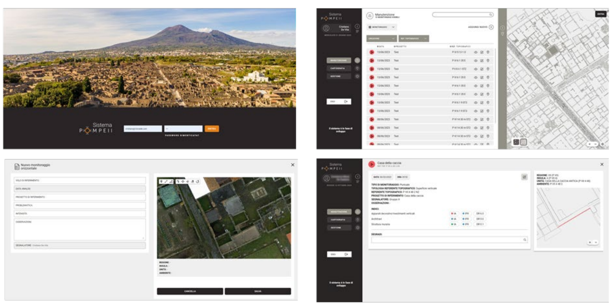
Figure 7. Web-based software for Local Assessment Level.

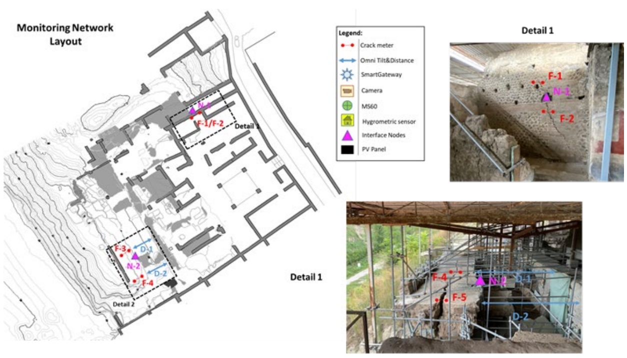

Figure 8. Example of monitoring networks into the Archaeological Park of Pompeii.

3. Method for Integrating GA with Satellite Data

GA can be significantly enhanced by integrating the processing of drone-acquired data with satellite data, specifically SAR (Synthetic Aperture Radar) data, which, when processed using techniques such as satellite interferometry, allow for millimeter-precision measurements of ground and structural movements. This is particularly useful in sites subject to subsidence, where monitoring ground movements is essential to prevent structural damage and ensure safety.
The combined use of drone and satellite data provides a more detailed and accurate view of the site's condition, improving the ability to detect even minimal displacements that might go unnoticed with other techniques. Furthermore, the analysis of SAR data can help identify areas with potential risks, such as zones more prone to settlement or instability, allowing for prompt intervention to prevent serious damage.
This section will describe the methodology used to process SAR data and the calculation process to determine the gradient of vertical displacement velocities along the vertical faces of the insulae. The gradient is useful for identifying areas at risk of damage, which then require more attention in DA.

3.1 Satellite Interferometry

Interferometric techniques allow for the measurement of the deformation component along the direction connecting the sensor to the ground target, i.e., along the satellite’s line of sight (LOS). The technique detects whether the target on the ground is approaching or moving away from the satellite, enabling the monitoring of surface ground movements.
The displacement measurements provided by multi-temporal SAR interferometric techniques capture only one component of the deformation vector resulting from the displacement. The more the direction of the actual deformation vector deviates from the line of sight, the smaller the deformation component detected by the satellite will be. In cases of deformation occurring perpendicular to the LOS, the measurement is null (Hu et al., 2014). This is a critical aspect for detecting movements, as some surface deformations may remain undetected if oriented perpendicular to the satellite’s line of sight. Thus, one of the limitations of this technique is that an interferogram measures only one component of surface deformation along the satellite’s line of sight. However, by using multiple acquisitions and applying advanced techniques such as multi-temporal analysis, a more complete representation of the site’s movements and deformations can be obtained.
In particular, the PSInSAR™ (Persistent Scatterers Interferometric Synthetic Aperture Radar) technique, patented by the Polytechnic University of Milan, utilizes all available SAR acquisitions of a given area of interest and identifies those targets (PS - Permanent Scatterers) that maintain stable electromagnetic characteristics over time. For each of these targets, a historical series of displacements can be reconstructed with millimeter-level precision (mm/y) (Bert, 2006). SAR satellite platforms follow ascending and descending orbits; due to Earth’s rotation and the fact that the SAR antenna is always oriented on the same side relative to the velocity vector in the orbital plane, a region may be illuminated from the East during descending passes (from North to South) and from the West during ascending passes (from South to North). By combining acquisitions from both East and West, in addition to reducing many spatial distortions, it is possible to calculate the vertical displacement component, which is particularly useful for analyzing subsidence phenomena (D’Aranno et al., 2021).

3.2 Analysis of Satellite Data

The average displacement velocity of a single Persistent Scatterer (PS), expressed in mm/year and referenced to a stable area (Reference Point), is calculated along the LOS for the time interval between the first and last acquisitions of the SAR image stack, which refers to a series of SAR images acquired over the same area at different times.

It is important to emphasize that the displacement measurements are relative, both in time (with respect to the reference acquisition, the master image) and in space (with respect to the Reference Point).
This measure allows the determination of the vertical component of the average displacement velocity, relative to the common period between ascending and descending acquisitions, at the nodes of a grid oriented according to the directions of the geographic or cartographic grid and with a specified grid spacing.
The average displacement velocities are obtained through linear regression on the deformations measured at the various acquisitions over the examined time period. To evaluate the magnitude of displacements relative to the surrounding area, which are indicative of differential subsidence potentially damaging to structures, the displacement gradient can be calculated. The displacement gradient provides a measure of the spatial distribution of these vertical displacements. A high gradient indicates a rapid change in displacement velocity over a short horizontal distance, while a low gradient suggests a more gradual change.
The analyses are performed for each individual insula inside the PAP. The vertical parameter traces of each insula are already available, having been digitized in a GIS environment as polygonal shape files, based on orthoimages produced from photogrammetric UAV-acquired imagery.
The calculation process follows these steps, implemented in MATLAB, and described in detail in the following subsections:

- Calculation of the vertical displacement gradient, separated for each direction of the grid, specifically along latitude and longitude.
- Calculation of the principal directions of the insula.
- Calculation of the gradient according to the principal directions.
- Generation of shape files (.shp) for the computed gradient vectors.

The resulting vector files are imported into QGIS and WebGIS environments for further visualization and analysis.

3.2.1 Linear gradient calculation

The calculation of the linear gradient (g) allows for determining the variation in displacement velocity along a specific direction, between two grid nodes. The gradient in the chosen direction is calculated as the difference in vertical displacement between the nodes, divided by the node spacing. The equation is as follows:

$$g = \frac{S_{i+1} - S_i}{D_{i,i+1}} \tag{1}$$

where S_i represents the vertical displacement at the i-th node, and $D_{i,i+1}$ is the distance between two consecutive nodes along the analyzed direction.
In this way, the velocity gradient of displacement is calculated for each pair of nodes, considering the grid's directional orientation.

3.2.2 Principal directions calculation

To calculate the gradient along the ancient masonry walls of the insulae, it is necessary to identify the directions of the walls within each insula. Since most insulae have walls arranged heterogeneously and not in parallel, it is useful to estimate an orthogonal axis system that best represents the overall directions of the walls of the entire insula.
The components parallel to the walls of each insula were identified by calculating the principal directions, following the computational steps outlined below:

1. Discretization of the boundary polylines from the shapefile using points with a 10 cm spacing.
2. Calculation of the direction angles for each pair of consecutive points.
3. Calculation of the circular median of the direction angles, accounting for the circular nature of the angles (ranging from 0 to 2π). This direction will be referred to as the Median Direction.

The circular median is given by the following equation:

$$\vartheta_m = \arg\min_{\vartheta} \sum_{i=1}^{n} \min\left(\left|\vartheta - \vartheta_i\right|, 2\pi - \left|\vartheta - \vartheta_i\right|\right) \tag{2}$$

where ϑ_i are the direction angles for each consecutive point pair (ranging from 0 to 2π), and ϑ is the angle that minimizes the sum of angular distances.

4. Calculation of the orthogonal direction to the median direction in order to determine an orthogonal axis system for each insula, representing the most frequent directions of the ancient masonry walls of the analyzed insula.

The median is preferred over a more robust method, such as Principal Component Analysis (PCA), because it better handles the circular nature of the data and provides a simpler, more intuitive solution.

3.2.3 Gradient calculation along principal directions

For each insula, the principal directions are calculated as previously described. The gradient calculation along these directions is carried out in two steps:

1. Determination of the centroid (G) of the four nodes (n) that define each grid cell.
2. Selection of the nodes whose centroid falls within the outer boundary of the insula.

The gradient along the principal directions of the planimetric grid is calculated as the slope of the lines formed by the intersection of the vertical plane with the principal directions and the lines passing through the grid nodes.
The lines passing through the grid nodes have a slope that represents the gradient calculated linearly for each node pair, as described in section 3.2.1.
This approach allows for an accurate determination of the velocity variations along the principal directions of the grid. Figure 9 shows a graphical representation of the gradient calculation along the median direction (g_m) and along the direction orthogonal to the median direction (g_o).
The gradient values are associated with the centroid of the four nodes defining each grid cell and are represented by vectors (v_g and v_o), with magnitude equal to the absolute value of the gradient and direction corresponding to the sign of the gradient.

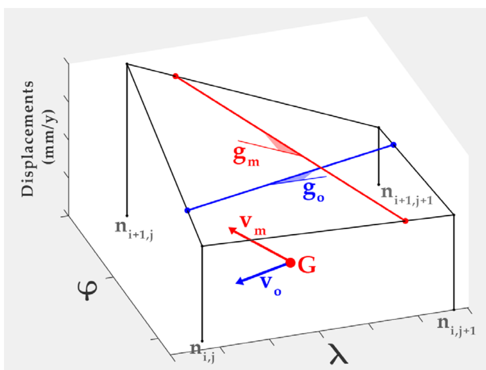

Figure 9. Gradient calculation scheme along the median direction (in red) and the orthogonal direction (in blue).

4. Results

The interferometric analysis was performed by e-GEOS using the PSInSAR™ technique on SAR data acquired from the COSMO-SkyMed mission, operated by the Italian Space Agency (ASI). In particular the Satellite Data were available within the national monitoring project led by the Colosseum Archaeological Park (D.M. 19/2019).
This analysis focused on the Pompeii area, with data collected in both ascending and descending geometries between April 12, 2014, and August 7, 2024. The ascending dataset comprises 152 SAR images, while the descending dataset includes 169 images, both featuring a ground resolution of 3 m × 3 m.
For the ascending geometry, images captured from April 12, 2014, to August 3, 2024, were analyzed, using April 26, 2019, as the master image. In contrast, the descending geometry utilized a master image from September 16, 2018, with analyzed images collected between June 17, 2014, and August 7, 2024.
By integrating the displacements derived from the individual orbits, the vertical displacement component for the overlapping time period of June 17, 2014, to July 30, 2024, was calculated. The vertical displacement components were mapped onto a grid with a cell size corresponding to the average resolution of the utilized images, ensuring that at least one PS from both ascending and descending datasets was present in each cell. The average of the ascending and descending measurements was computed for each cell, serving as input for the subsequent component decomposition process to extract the vertical displacement.
Given that the ascending and descending SAR data are processed at maximum resolution without under-sampling, their spatial density enables the derivation of vertical deformation components within grid cells of 10 m × 10 m resolution. The vertical displacements are temporally referenced to the first common acquisition date for both datasets.
Negative displacement values associated with the PS indicate movement away from the sensor in the context of LOS measurements, which corresponds to subsidence in the vertical component analysis. Figure 10 illustrates a map of the grid nodes along with their corresponding average displacement velocities, represented as the slope of the linear regression of the deformations measured across the various acquisitions during the study period. The analysis reveals that the average vertical displacement velocities in the study area indicate regions experiencing a maximum subsidence rate of approximately 6 mm/year, alongside areas exhibiting a maximum uplift of around 2 mm/year.
Building on the previously described data, we carried out the gradient computation independently for each insula. Using this data as input, we applied the methodology outlined above, and the results are visualized in Figure 11 using the QGIS environment. Specifically, the map displays the results for insula 8 of Regio I.
The median principal direction, shown in red, was determined by computing the circular median of the direction angles of the segments that make up the vertical façades, which were discretized every 10 cm. The median direction has an angle of 237,15°, while the orthogonal direction, shown in blue, corresponds to an angle of 327,15°.
The arrow length, representing the gradient vector along either the median or the orthogonal direction, is proportional to the gradient magnitude, and its orientation depends on the sign of the gradient.
The arrow points toward the location with the higher vertical displacement. To clarify the adopted convention, Figure 11 includes an isolated example referring to the centroid (G4).
In this case, both gradients are positive, and the arrows therefore point toward the highest vertex of the parallelepiped defined by the mesh vertices under analysis, in agreement with the adopted coordinate system.
For the insula under investigation, the gradient along the median direction ranges from approximately -0,06 to 0,06 mm/m/year, while along the direction orthogonal to the median it ranges from approximately -0,08 to 0,06 mm/m/year.
As shown in Figure 11, the use of the circular median yields consistent and meaningful results, despite the heterogeneous orientation of the façades within the insula.

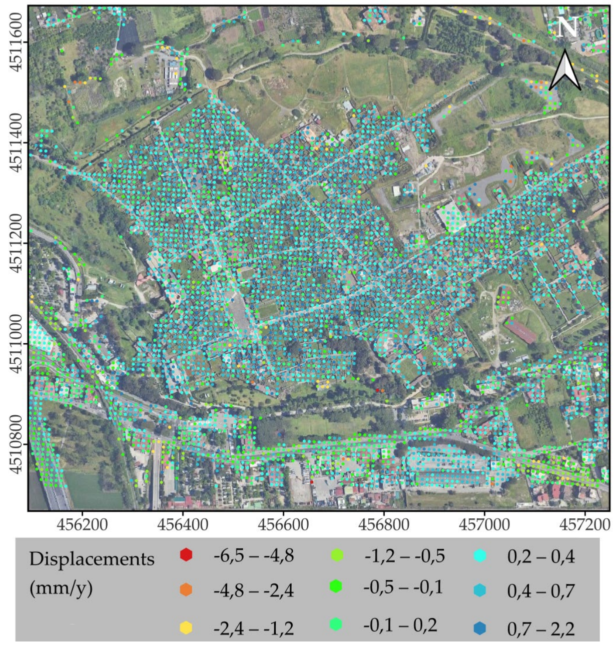

Figure 10. Average annual vertical displacement map (mm/year), referenced to EPSG:32633 (e-GEOS - national monitoring project led by the Colosseum Archaeological Park, D.M. 19/2019). Base map from Google.

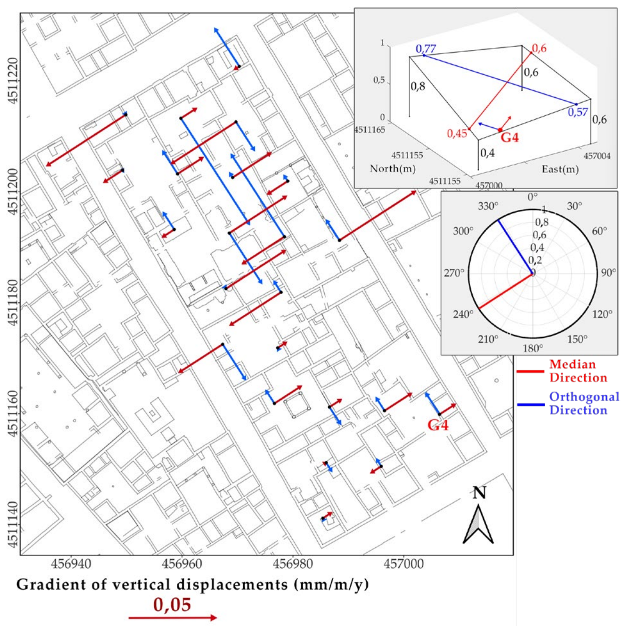

Figure 11. Gradient map along the principal directions, EPSG: 32633.

5. Conclusions

The interferometric analysis conducted on the Pompeii area has demonstrated that the PSInSAR^{TM} technique can provide significant support in emergency management and routine maintenance. SAR images acquired from the COSMO-SkyMed mission, captured in both ascending and descending geometries, allowed for accurate mapping of vertical displacements, effectively identifying areas of subsidence and uplift.

In particular, the analysis of gradients along the median and orthogonal directions offered a clear representation of the deformations, highlighting regions that may present greater concerns and warrant further in-situ analysis. This approach not only provides detailed insights into the structural changes but also helps prioritize areas that require immediate attention or additional monitoring.

This technique, when combined with drone-based imagery for general panoramic views and further data analysis through artificial intelligence (AI) applications, can play a pivotal role in identifying and addressing critical issues. It also enables the identification of conditions that necessitate in-depth evaluations, thereby contributing to more effective emergency management and preventive maintenance strategies.

A systematic, repeatable monitoring approach, such as the one implemented at Pompeii, is crucial for ensuring the long-term preservation of the site. By integrating such methodologies, we can ensure continuous monitoring and timely intervention, enhancing both the resilience and conservation of cultural heritage sites.

References

Amato V., Covolan M., Dessales H., Santoriello A., 2022. Seismic Microzonation of the Pompeii Archaeological Park (Southern Italy): Local Seismic Amplification Factors, Geosciences, vol.12, 275, https://doi.org/10.3390/geosciences12070275.

Bevilacqua A., Macedonio G., Neri A., Orsi G., Petrosino P., 2022. Volcanic Hazard Assessment at the Campi Flegrei Caldera, Italy, Campi Flegrei. Active Volcanoes of the World. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-37060-1_12.

Bert, M. K., 2006: Radar interferometry: persistent scatterers technique, The Netherlands, Springer.

D'Aranno, P. J. V., Di Benedetto, A., Fiani, M., Marsella, M., Moriero, I., Palenzuela Baena, J. A., 2021. An Application of Persistent Scatterer Interferometry (PSI) Technique for Infrastructure Monitoring, Remote Sensing, 13.

Decision (EU) 2017/864 of the European Parliament and of the Council of 17 May 2017 on a European Year of Cultural Heritage (2018).

Decree-Law no. 91 of 8th August 2013, President of the Republic, Urgent provisions for the protection, valorisation and relaunch of cultural assets and activities and tourism.

D.M. 19/2019, Monitoraggio Plurisistemico anche mediante l'analisi satellitare del patrimonio archeologico e monumentale nazionale, tra i parchi archeologici del Colosseo, di Pompei, di Ostia antica, di Paestum, di Ercolano, dei Campi Flegrei. Finanziamnto: A.F. 2019 – Capitolo n. 2.1.2.035, Delibera n. 8 del 30/10/2019 del capofila Parco Archeologico del Colosseo.

European Commission: Directorate-General for Education, Youth, Sport and Culture, 2019. European framework for action on cultural heritage, Publications Office, https://data.europa.eu/doi/10.2766/949707

Frangopol D. M., Liu M., 2007. Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost, Structures and Infrastructure Systems, Taylor & Francis, Milton Park, vol. 3, 29-41, DOI: 10.1080/15732470500253164.

GPP Projects, Progetti G.P.P. - Pompeii Sites.

Hosagrahar, J., Soule, J., Fusco Girard, L., Potts, A., 2016. Cultural heritage, the UN Sustainable Development Goals, and the new urban agenda. BDC. Bollettino Del Centro Calza Bini, 16(1), 37-54. https://doi.org/10.6092/2284-4732/4113.

Hu, J., Li, Z. W., Ding, X. L., Zhu, J. J., Zhang, L., Sun, Q., 2014. Resolving three-dimensional surface displacements from InSAR measurements: A review, Earth-Science Reviews, 133, 1-17, https://doi.org/10.1016/j.earscirev.2014.02.005.

IM-SAFE, 2020, Horizon 2020 research and innovation programme under grant agreement No 958171, https://im-safe-project.eu.

Latorre D., Di Stefano R., Castello B., Michele M. Chiaraluce L., 2023. An updated view of the Italian seismicity from probabilistic location in 3D velocity models: The 1981–2018 Italian catalog of absolute earthquake locations (CLASS), Tectonophysics, Elsevier, Amsterdam, vol. 846, ISSN: 0040-1951.

Law no. 112 of 7th October 2013, President of the Republic, Conversion into law, with amendments, of the decree-law of 8 August 2013, n. 91, containing Urgent provisions for the protection, valorisation and relaunch of cultural assets and activities and tourism.

Mauro A., 2019. From the extraordinary nature of the great Pompeii project to planned conservation, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2nd International Conference of Geomatics and Restoration, Milan, vol. XLII-2/W11.

Miele F., 2011. La conservazione della memoria materiale e immateriale. Sistemi informativi di catalogo e territoriali in Campania, Archeologia e Calcolatori, vol. 22 p. 7-34, ISSN 1120-6861.

Ministry of Cultural Heritage and Activities and Tourism, Decree of 12 January 2017 (OJ 10/03/2017), Adaptation of special superintendencies to international standards regarding museums and places of culture.

Ministry of Infrastructure and Transport, 2020 Ministerial Decree 578/2020, Adoption of Guidelines for Risk Management of Existing Bridges and for the Definition of Requirements and Indications relating to the Dynamic Monitoring System, Rome, Italy.

Open Pompeii, The public digital archive of the heritage data of the Archaeological Park of Pompeii, POMPEII (pompeiisites.org).

Osanna M., Rinaldi E., 2018. Planned conservation in Pompeii: complexity and methodological choices, Journal of Cultural Heritage Management and Sustainable Development, Emerald Group Publishing, Bingley, vol. 8 n.2, 111-129, https://doi.org/10.1108/JCHMSD-05-2017-0025.

Osanna M., 2020. Il grande progetto Pompei per l'insula Occidentalis, Pompeii Insula Occidentalis Conoscenza, Scavo, Restauro e Valorizzazione, L'Erma di Bretschneider, Roma, 13-14, ISBN: 9788891316103.

Petzet M., 2009. International principles of preservation, International Council on Monuments and Sites, Hendrik Bäßler Verlag, Berlin, vol. 20, ISBN 978-3-930388-54-7.

Petti L., Lupo C., De Gaetano C.M., 2023. A Methodological Framework for Bridge Surveillance, Applied Sciences, 13.8, 4975, https://doi.org/10.3390/app13084975.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.

Petti L., Lupo C., D'Angelo T., Dallocchio P., Guizzetti D., 2024. An Innovative Monitoring Strategy of Ancient Temples made of Rigid-Block Structures, Procedia Structural Integrity, Elsevier, vol. 64, 637-644

Petti L., Zuchtriegel G., Lupo C., Calvanese V., De Gaetano C.M., 2024. A sustainable monitoring approach to manage complex archaeological sites – The example of Pompeii, Procedia Structural Integrity, Elsevier vol. 64, 629-636.

Picone R., Osanna M., 2018. RESTAURANDO POMPEI. Riflessioni a margine del Grande Progetto, L'Erma di Bretschneider, Roma, ISBN: 978-88-913-1727-8.

Pregnolato M., 2019. Bridge safety is not for granted–A novel approach to bridge management, Engineering Structures, Elsevier, Amsterdam, vol. 196, DOI: https://doi.org/10.1016/j.engstruct.2019.05.035.

Romao X., Bertolin C.,2022. Risk protection for cultural heritage and historic centres: Current knowledge and further research needs. International Journal of Disaster Risk Reduction ,67: 102652.

Sesana E., Gagnon A., Ciantelli C., Cassar J., Hughes J., 2021. Climate change impacts on cultural heritage: A literature review. WIREs Climate Change, 12. DOI: 10.1002/wcc.710.

Smart@Pompei, Smart Pompei - Pompeii Sites.

Charter, V., 1964. International charter for the conservation and restoration of monuments and sites. Venice, Italy.

UNESCO, 2010, Managing Disaster Risks for World Heritage, ISBN: 978-92-3-104165-5.

UNESCO, 2013, Managing cultural world heritage, ISBN: 978-92-3-001223-6.

UNI 10144:2006, 2006, Classification of Maintenance Services.

UNI 10224:2007, 2007, Maintenance – Process, sub-processes and main activities – Fundamental Principles.

Zuchtriegel, G., 2022. Paestum. I luoghi dell'archeologia, Roma.

Zuchtriegel G., Petti L., Nesticò A., Maselli G., Calvanese V., Onesti A., Spinosa A., 2024. Economic and management issues concerning archaeological sites: cost analysis, study of tourist flows and sustainability perspectives for the Archaeological Park of Pompeii, Valori e Valutazioni, 36, 101- 124; https://doi.org/10.48264/VVSIEV-20243607