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# MONITORING METHODS AS A PREVENTATIVE MEASURE. THE EXAMPLE OF THE *CAPITOLIUM* IN OSTIA ANTICA

*Fin dall'antichità, le coste del Mediterraneo hanno subito varie catastrofi, che hanno portato allo sviluppo di piani di manutenzione e riparazione, oltre che al miglioramento di soluzioni preventive. Da varie civiltà emergono strategie di resilienza per adattarsi ai disastri naturali e ai cambiamenti ambientali. In questo contesto, i disastri hanno avuto un forte impatto sull'antico porto romano di Ostia Antica. Le scoperte archeologiche di questa antica "città galleggiante" ne rivelano la resilienza e ci aiutano a costruire una cronologia delle calamità. Di conseguenza, la valutazione delle condizioni di conservazione e l'esame delle tecniche di costruzione sono gli obiettivi principali che richiedono un approccio interdisciplinare. Un metodo esemplare è illustrato nel contributo, basato su diverse tecniche di monitoraggio non invasivo, concepite per valutare lo stato di conservazione del Capitolium, un progetto edilizio adrianeo in Ostia Antica. Mentre i rischi naturali sono difficili da prevedere, le vulnerabilità possono essere affrontate, riducendo il rischio di catastrofi. La registrazione e l'analisi dei dati ambientali consente di valutare tali rischi. L'articolo evidenzia i risultati di un primo controllo incrociato di dati e informazioni ottenuti negli ultimi sette anni per analizzare le deformazioni strutturali, permettendo di contribuire alla cronologia storica e di garantire una conservazione preventiva mirata per l'accessibilità e le strategie di manutenzione.*

## Introduction

Risk assessments are a fundamental first step in identifying effective mechanisms for climate change adaptation and disaster management. Climate change increases risks, making events more frequent and intense, and thus increasingly complex and challenging to manage.

This has resulted in increased attention and funding for large-scale development projects focused on continuous monitoring in disaster management plans. Long-term monitoring helps to increase the knowledge of the real behavior of the structure and in the planning of maintenance interventions. In urban contexts, traffic-induced vibrations accelerate the deterioration processes, significantly increasing vulnerability to static and dynamic actions and even leading to a sudden collapse under seismic activities. Similarly, adequate seismic and environmental monitoring of non-urban contexts ensures the development of prevention and maintenance strategies. Natural aging of the materials, associated with erosion phenomena due to wind and rain, as well as pollutants and the effects of thermal cycles, determines changes and continuous deterioration of the exposed surfaces with a significant reduction of


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the material strength and structural capacity. Preventive conservation aims to prevent or minimise the risk of irreversible damage to cultural artifacts caused by environmental factors they are exposed to, such as relative humidity, temperature, light, atmospheric and air pollutants, vibrations, etc. Structural Health Monitoring (SHM) is a rapidly developing sector that vastly improves assessing the structure's current condition for preservation strategies based on modal characteristics (frequency, mode shapes, curvature, the dynamic flexibility matrix) correlated with damage[1]. There is a recent increase in environmental monitoring projects for cultural heritage; among them, the contributions of Soleyman[2] and Karathanassi[3] provide an insightful overview of various Structure Health Monitoring measurement methods. They compare sensor-based and remote sensing methods, providing a detailed analysis of their advantages and disadvantages. Karathanassi's emphasis on Hyperion Project 3, targeting 'routine monitoring' of cultural heritage sites, was presented as pilot studies in Rhodes, Granada, Venice, and Tønsberg at the latest EGU General Assembly in Vienna. The project covered displacement and land cover change detection maps, flood monitoring maps, three-dimensional models of assets, and detailed assessments of deterioration and material loss on specific facades in Rhodes. The findings highlight the innovative approach that remote sensing can take to preserve. Recent advances in the techniques of SHM have also enhanced the ability to detect building damage from natural disasters due to large-scale open-source datasets. An essential part of this research approach is accessing satellite image databases for forecast calculations due to their multispectral channels, high resolution (VHR), and geo-tags. Government agencies like NASA and the ESA (European Space Agency) and companies such as DigitalGlobe supply these resources for training to involve the communities, not just institutions. Being able to access and be aware of the country's climate status increases awareness of environmental issues and encourages prevention.

Damage assessment and remote monitoring are also crucial in documenting and planning future protection strategies in geopolitical settings. Assessing architectural heritage damage right after a conflict can record key details, including the extent, severity, frequency, and nature of the damage, which are all essential for rescue, humanitarian aid, and rebuilding activities in affected areas. Satellite imagery-based assessments mainly focus on significant and catastrophic structural damage, not on minor building issues. Experts conducted a noteworthy damage assessment in the Gaza Strip using satellite imagery[4], documenting the monument and the type of dynamic collapses[5].

Among innovative remote sensing techniques, Rezaeian[6] outlines the application of multi-temporal high-resolution optical images to assess local building damage. He emphasised analysing data from space-borne and air-borne sensors to track changes over time and describe environmental characteristics dynamically. Passive optical and photogrammetric cameras are simpler, less expensive, and more reliable than active sensors. In certain situations, these technologies, along with wireless sensors and innovative drone approaches (such as motion magnification analysis) provide a wide range of data and information. This can improve our understanding of the static and dynamic behavior of historical buildings, aiding in assessing preservation plans and maintenance interventions[7].

Optical fiber sensors are another advanced technology that has emerged in the last few years. Long-term static monitoring necessitates highly accurate and stable systems capable of recording measurements at regular intervals over extended periods. Additionally, sensors should be installed with minimal impact on the aesthetics and functionality of the structure being tested. Some examples of case studies in Switzerland and Italy were already presented in Glisic[8]. From many points of view,

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[1] Buffarini *et al.* 1996; Clemente, Rinaldis 2005.
[2] Soleyman *et al.* 2023.
[3] Karathanassi *et al.* 2024.
[4] https://unitar.org (last access December 20th, 2024).
[5] Pecchioli 2021.
[6] Rezaeian 2010.
[7] Liu *et al.* 2005; Fioriti *et al.* 2022.
[8] Glisic *et al.* 2007.

fiber optic sensors are the ideal transducers for civil structural monitoring in general and non-intrusive nature and multiplexing capabilities.

Among relevant innovative projects, the European Commission funded SMooHS (Smart Monitoring of Historic Structures) as part of the 7th Framework Program in December 2008. The project team delivers insights into wireless monitoring technologies based on minimally invasive installation methods, long-term performance, versatile multi-sensor platforms compatible with various sensor technologies, and comprehensive data analysis and interpretation techniques[9].

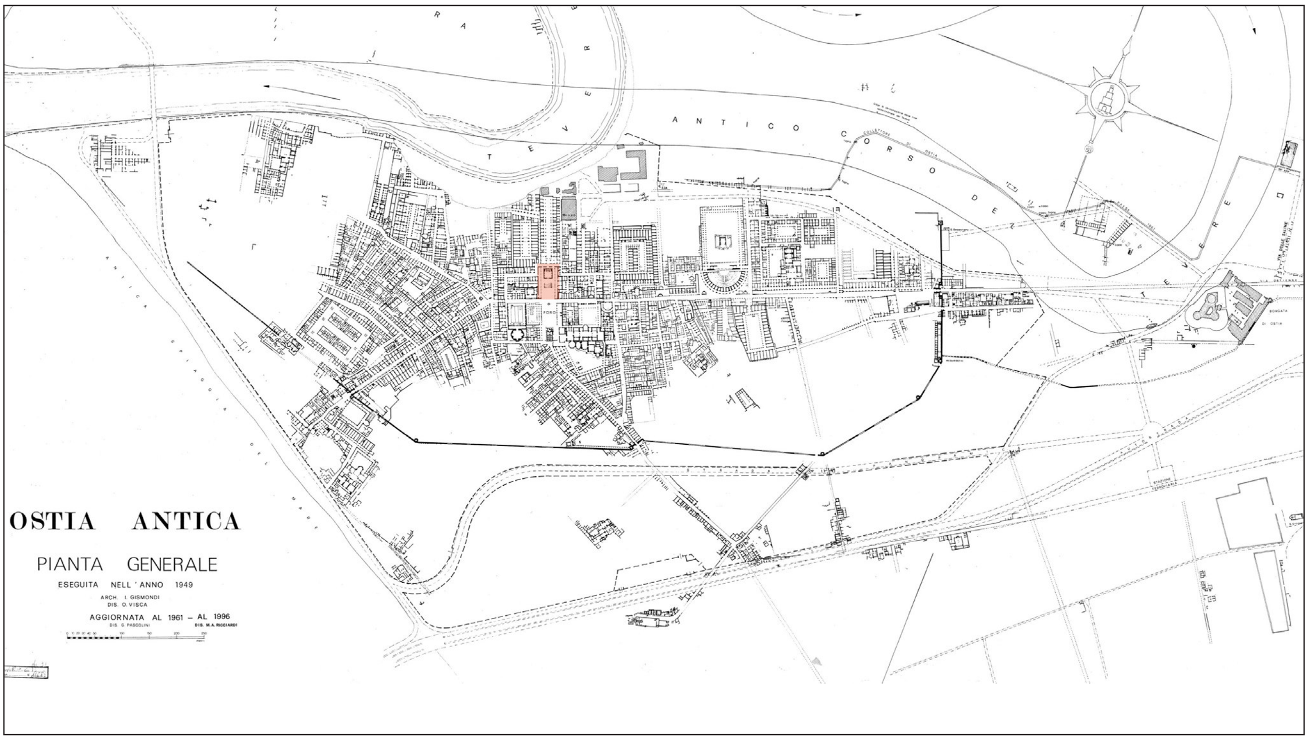
Within this framework, the Archaeological Park of Ostia Antica is participating in a national-scale project related to all national archaeological parks, the 'Copernicus project,' involving instrumental and satellite monitoring of territorial assets. According to the collaboration protocol, the monitoring plan is part of the 'Protocol of collaboration for implementing the national project of monitoring and programmed maintenance of the archaeological and monumental heritage' coordinated by the Colosseum Archaeological Park. MIC_PA-OANT n. 4480 of 15.10.2019. A plan concerns 'the multi-systemic monitoring also through satellite analysis of the national archaeological and monumental heritage (DM 19/2019) between the Archaeological Parks of the Colosseum, Pompeii, Ostia Antica, Paestum, Herculaneum, Campi Flegrei'. The collaboration protocol facilitated the sharing of various monitoring parameters, including satellite analysis, which were identified by each park according to its conservation and archaeological protection needs. Parameters identified include soil and structure deformation, ground cover, climatic conditions, water table levels, and vegetation stress. In these parameters, structural safety, climate control in confined spaces, and groundwater levels are monitored using on-site instruments. The proposed monitoring plan identifies priorities based on criteria such as the state of preservation, critical static conditions, architectural, historical, and artistic meanings, morphological and architectural characteristics, representativeness of specific problem types in certain areas, position, visibility, and potential danger related to visitor flows, as well as the varying difficulty of conducting periodic visual inspections. One of its aims was to prioritise monitoring a high and more fragile cultural heritage. In 2021, the prominent Hadrianic monument, the *Capitolium*, located in the Forum of Ostia Antica, was significant due to frequent environmental issues in the archaeological park and evidence of seismic activity (*fig.* 1).

## 1. Interdisciplinary investigations for damage assessment for the *Capitolium*

Throughout history, many areas around the Mediterranean have experienced frequent calamities. Ostia Antica, an ancient Roman harbour built on sandy soil, was regularly impacted by natural disasters like flooding, earthquakes, and changes in the groundwater table, leading to coastline alterations. Civil and monumental buildings were constructed on unstable ground, resulting in repeated damage and subsequent repairs.

The first step for preventive conservation is risk assessment, and the *Capitolium* has undergone noninvasive investigations over the past seven years. Risk identification is the systematic use of available information from various sources to study risk by identifying hazards and vulnerability factors. *Capitolium* has endured various stresses throughout its history, including natural disasters like erosion, collapse of load-bearing walls[10], and subsidence. Human-induced events have also impacted its preservation, leading to its vulnerability due to spoliation and reuse[11]. Collected data is being cross-checked to understand the relationship between structures and environmental features. Evidence of structural reinforcements, repairs, and construction methods provides disaster prevention information to speculate that the monument's lifespan since its construction began required structural reinforcement

[9] Abruzzese *et al.* 2009.
[10] Trockels forthcoming.
[11] Gilbert 1912; Valenti 2016; Carcopino 1910, p. 403.




1. PLANIMETRIC MAP OF OSTIA ANTICA SHOWING THE LOCATION OF THE *CAPITOLIUM* (elaboration by Authors from I. Gismondi, in CALZA 1953).

solutions. The investigations carried out were the following:

- in 2016, *Capitolium* was one of the monuments studied for its collapse dynamics[12], for traces of possible seismic events evident as with other instances in Ostia (*fig.* 2, A);
- from 2016, Kyushu University performed a detailed laser scanner survey, repeating it periodically until 2023 (*fig.* 2, B);
- in 2017 and 2019, as part of a research project supported by Gerda Henkel Stiftung, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) conducted seismic investigations within the monument to identify amplification phenomena (Site Effects).
- environmental monitoring started in 2022 by the Archaeological Park of Ostia Antica to track cracking deformation in the three barrel-vaulted podium rooms (*favissae*) is ongoing[13].

## 1.1 Carpentry repairs like as a maintenance practice

In Hadrian's time, architecture underwent significant stylistic and material changes. He was celebrated for his intellectual interests and prioritised improving infrastructure as well as boosting brick manufacturing. Hadrian's architectural and cultural contributions highlight his importance in Roman history. He initiated several construction projects, including the *Capitolium*, which was built around 120 AD in the Forum area during his reign[14]. Like other Roman monuments of its era, the *Capitolium* reflects the dimensional ratios of the architectural order, lavish marble usage, and high-quality decoration, showcasing the exceptional craftsmanship

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[12] GHS: https://lisa.gerda-henkel-stiftung.de/seismologie_trifft_archaeologie?nav_id=7558 (last access December 20th, 2024).
[13] PECCHIOLI *et al.* 2018; PECCHIOLI *et al.* 2020.
[14] BADGELEY 1929, pp. 221-22; VAN BUREN 1906.

2. A. *CAPITOLIUM* (2024); B. LASER SCANNER SURVEY PHASE FROM THE *CAPITOLIUM* PODIUM (2024) (photo by L. Pecchioli)

seen in other significant contemporary Roman buildings[15]. The most basic technique used for constructing the concrete core of a wall with brick courses, known as *Opus Testaceum*, was employed for the *Capitolium*[16]. The monument has four barrel-vaulted rooms in *Opus Caementicium* in its podium (*favissae*), which show several repairs and a cracking framework. Masonry is a heterogeneous material with an orthotropic and varied nature, leading to complex mechanical behavior that's hard to analyse[17]. Typically, Roman vaults appear as inert monoliths supported by walls, with horizontal caementa courses forming a 'pseudo-continuum.' This is achieved through thin cohesive layers due to mortar and stone adhesion and moderate tensile strength in all directions[18]. The *Opus Caementicium* vaults are intended to function as a single monolithic structure, akin to a solid stone block, without imposing horizontal pressures on the retaining walls. Nonetheless, given their limited tensile strength, they can fracture and exert forces on the walls as separate blocks.

Through the detailed survey, a longitudinal section reveals subsidence phenomena in the podium due to foundation failures, notably in each room, which contributes to justifying the various and numerous reinforcement devices[19] (*fig*. 3, A-B-C).

Even externally vertical fractures at the top corners of walls indicate weak structural connections, leading to external rotation and detachment at the summit. Specifically, a significant crack traverses rooms with barrel vaults, likely originating from an ancient collapse under the Podium staircase, which probably immediately required the insertion of three supporting pillars. The crack extends through the entire thickness of the barrel-vaulted rooms, constructed using *Opus Caementicium* (*fig.* 4). It exhibits compression damage near the stairs. It is located at the peak of the inner arch supporting the staircase.[20].

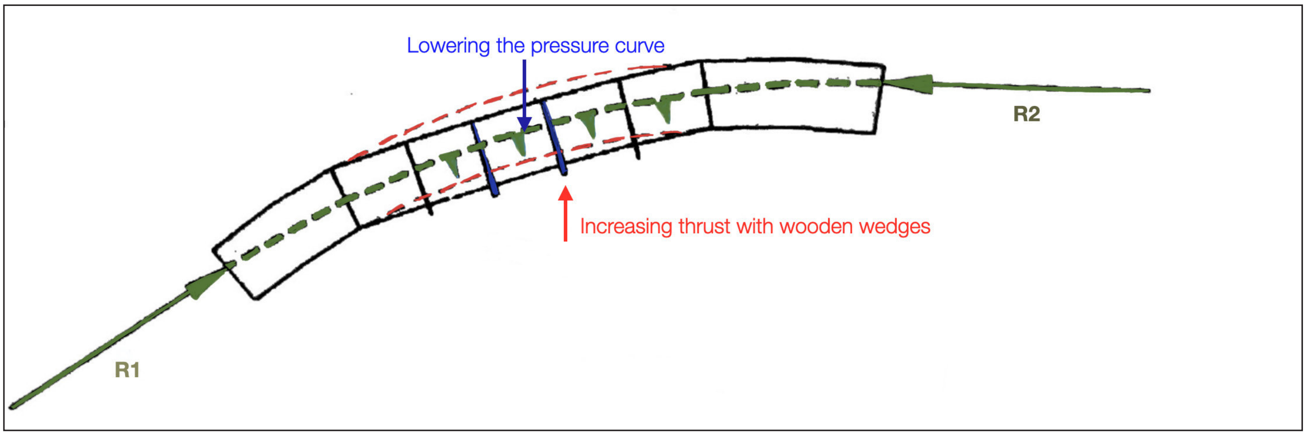
Various interventions include inserting wooden wedges at different heights to adjust the original curvature and counter structural deformation. One of the most common historical and modern techniques is to insert large reinforcing brick sub-arches to stabilize the deformed barrel vaults (*fig.* 3, B). Following initial assessments, the vault's depression indicates the entire ceiling's instability due to shutter settlement[21]. This approach, resembling a maintenance practice, includes placing wooden wedges into cracks in the vaults' intrados and sealing them with cement, exemplifying modern carpentry techniques. Such a choice represents a temporary measure at construction sites, often used by ancient builders' restoration and repair techniques instead of demolition. The aim is to restore the pressure curve within the middle third by increasing thrust and enhancing structural integrity. These interventions stabilise specific sections and offer cost-effective and efficient carpentry solutions dating back to ancient times, the Middle Ages, and the present day.

### 1.2 First Observations using Point Cloud Data

Due to the westward change of the Tiber Delta over time, the ancient harbour now lies within the coastal plain, buried beneath 20 to 40 meters of alluvial sediments. Measurement monitoring was necessary considering the environmental conditions and the obvious structural deformations. Field surveys using laser scanning were conducted[22] in 2016 and 2023 (*fig.* 5).

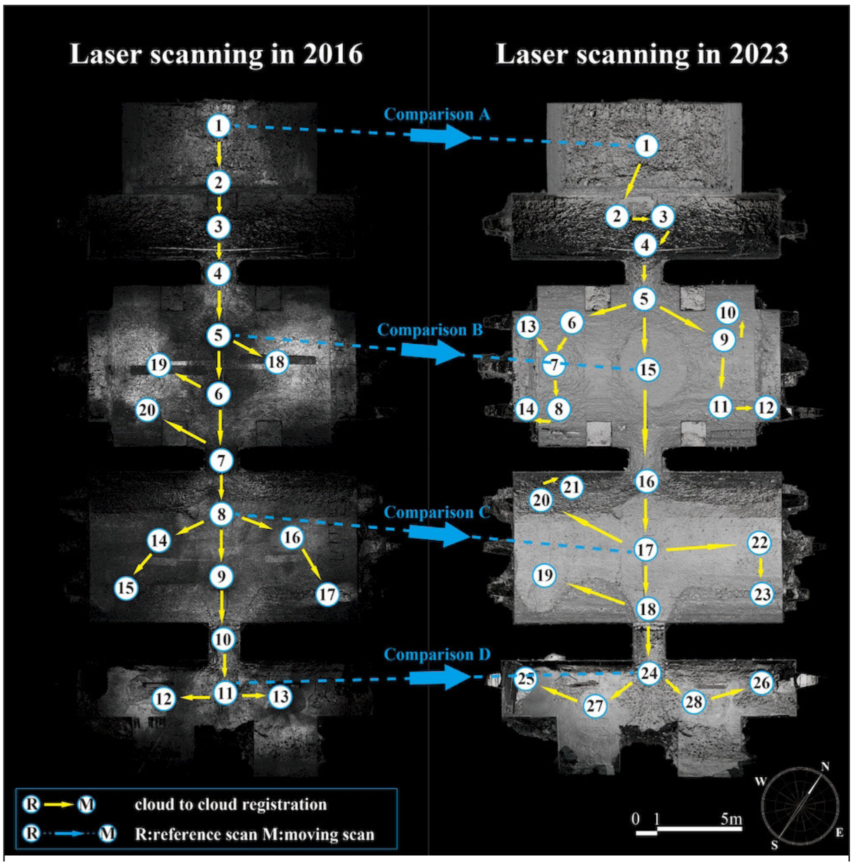
The point clouds were aligned so that the standard deviation of the histogram differences between each point cloud fell between 0,8 cm and 0,14 cm, creating point cloud data within the platform[23]. Instead of

[15] The current *Capitolium* was built during Emperor Hadrian's reign, and the Republican-era *Capitolium* already existed (Calza 1953, pp. 63-77; in Hory *et al.* 2017, see Note 6). Based on the archaeological and geophysical investigations, a temple overlaps with the stair area of the current *Capitolium*. The eastern wall of the first Temple has been excavated and can still be seen in front of the monument. Additionally, the ground of the *Capitolium* also overlaps with the walls and gates of the *Castrum*.
[16] Albo 2002.
[17] Heres 1983.
[18] Wittmann 1879.
[19] Giuliani 1990; Gangi 2023, p. 130.
[20] Albo 2002.
[21] Beranek 1988.
[22] Hori, Ogawa 2017.
[23] Ogawa, Hori 2019.

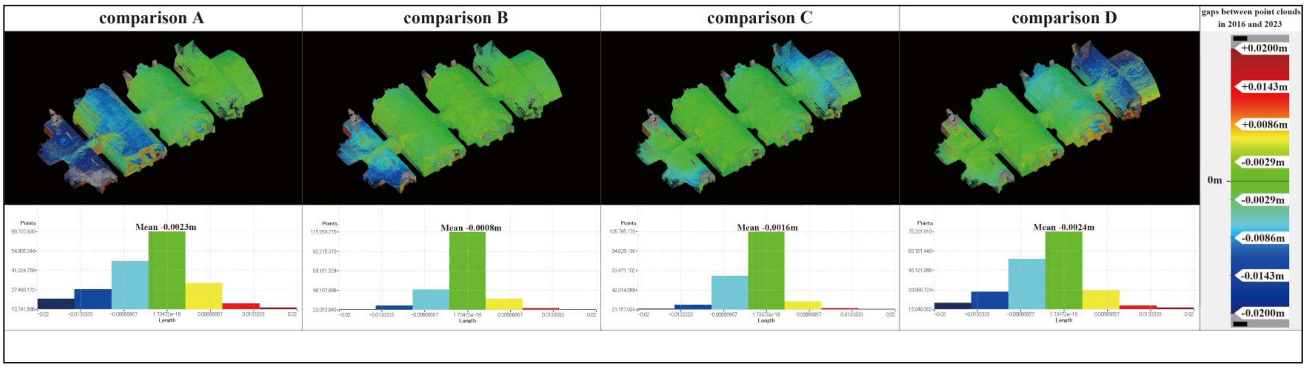



3. A. DETAIL OF THE INSERTION OF WOODEN WEDGES IN A CRACK IN THE INTRADOS OF THE VAULT; B. INTERVENTION SCHEME FOR REINFORCEMENT TO RESTORE THE PRESSURE CURVE WITHIN THE MIDDLE THIRD: LOWERING OF THE PRESSURE CURVE AND AN INCREASE IN THRUST; C. EXAMPLE OF STRUCTURAL REINFORCEMENT IN MASONRY ALONG A PERIMETER WALL (elaboration by L. Pecchioli)

4. CRACK UNDER THE STAIRS IN THE PODIUM (photo by L. Pecchioli)




5. SCANNER PLACEMENT AND PAIRINGS FOR THE POINT CLOUD ALIGEMENT (elaboration by T. Ogawa)




6. GAPS BETWEEN 2016 AND 2023 POINT CLOUDS FOR FOUR PAIRINGS (elaboration by T. Ogawa)

aligning the point clouds based on targets at GNSS points, shape matching was employed, utilising common sections of the point clouds for the least squares method. The point clouds used for alignment are denoted in *figs*. 5 and 6 as the reference scan, which fixes coordinates, and the moving scan, which shifts coordinates with each iteration.

To compare the results from point cloud data in this period, a point cloud from a similar location was selected for each year and aligned (comparison A in *figs*. 5 and 6). During the calculation using the least squares method, the relative positional coordinates of the overall point cloud data of the platform's interior remained unchanged. The comparison of 2016 and 2023 revealed displacements of about 2,0 cm in some areas, indicating that the data from both years did not perfectly match. Other pairs of reference and moving scans were selected from four rooms to eliminate the possibility that the 2,0 cm gap could have arisen from alignment errors. Reviewing the histograms for each pair, the results of comparison B, which showed the smallest displacement, are likely the most reliable.

The point cloud data from comparison B in 2023 indicates that the vaulted ceiling supporting the stairs and the floor has sunk by approximately 1,3 cm, with a maximum of 2,0 cm. These findings suggest that instead of the structures of the *Capitolium* displacing, it is more probable that the ground on which the monument was built, especially the ground under the stairs, has subsided. According to the results from other investigations, the last surveys aimed to detect any displacements in the barrel vaults and the floor within the platform by comparing point cloud data across these years[24] (*fig.* 7).

### 1.3 Seismic micro-zonation campaigns

Over the centuries, the *Capitolium* has suffered from various types of disasters. The ground's geological characteristics probably influenced a possible building's response to seismic shocks. In Ostia Antica, damage from seismic events seems to be varied, likely due in part to the alluvial soil's capacity to amplify seismic tremors[25], as seen in the metropolitan area of Rome[26]. A significant challenge in linking the observed damage to seismic activity is the need for historical seismicity data based on the five significant earthquakes between the V and IX century (443, 484, 508, 801, 847)[27]. In recent years, through the collaborative efforts of multiple research disciplines, like archaeoseismology[28], researchers have been reconstructing a historical timeline of seismic events by cross-referencing scientific data, archaeological findings[29], and archival records[30].

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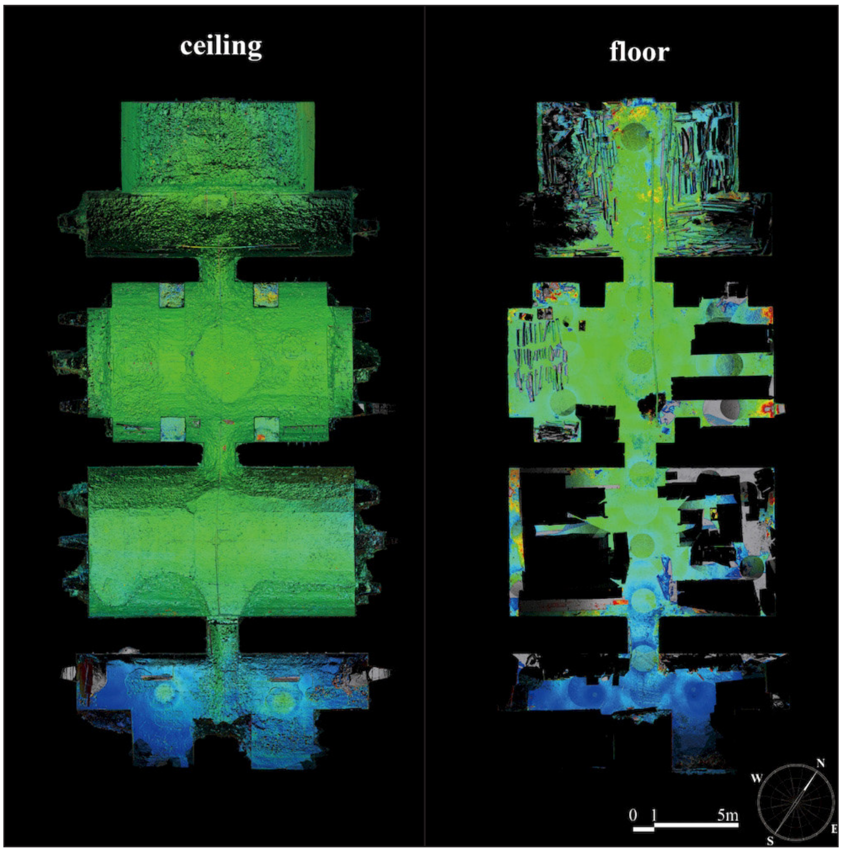
[24] Lim *et al.* 2022.
[25] Galadini *et al.* 2018.
[26] Canina 1856; Fea 1802; Guattani 1805; Kuhfeldt 1883.
[27] Marra *et al.* 2020.
[28] Pecchioli 2023.
[29] Borsari 1892; Vaglieri 1910, p. 13; Visconti 1858.
[30] Pecchioli *et al.* forthcoming




7. A COMPARISON OF THE VAULTED CEILING AND FLOOR SUBSIDENCE IS SHOWN (elaboration by T. Ogawa)

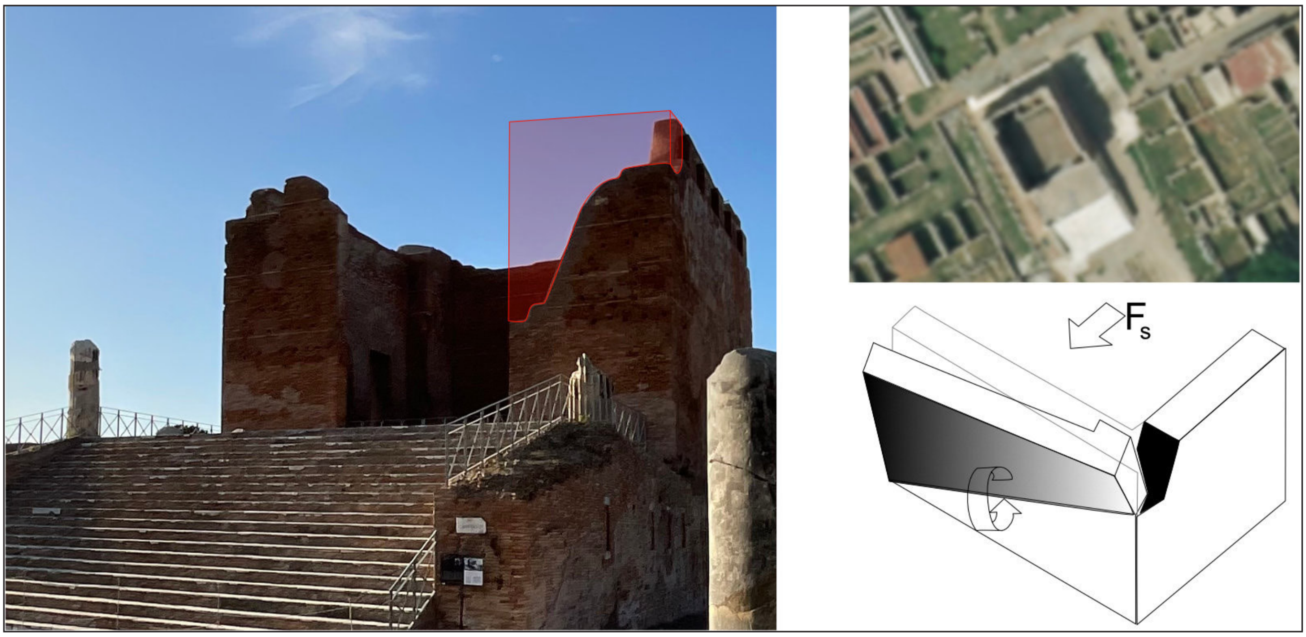
### 1.3.1 Site Effects

In 2017, due to the seismic effects identified around the *Capitolium*, targeted investigations were planned inside the monument. The urban settlement featured a square grid layout with parallel-oriented structures and was considered for a preliminary analysis[31]. The chessboard pattern, typical of Roman settlements, likely affected the direction of deformations during seismic events, influencing the extent of the damage.

In 2018, the first mechanical assessment of the masonry identified nine instances of seismic damage and the directions of the horizontal stresses responsible for their failure[32]. An initial analysis of collapse dynamics for seismic events, such as the kinematics of façade overturning, which led to the dislodging of a top portion of the corner wedge, was also hypothesised for the *Capitolium* (*fig.* 8). The result likely stems from multiple earthquakes occurring at different epicenters and propagating in various directions over time.

Between 2017 and 2019, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) carried on two seismic micro-zoning studies to assess *site effects*, offering insights into subsoil geology and its potential to amplify ground shaking locally. The first analysis of the selected case studies, including the *Capitolium*, was based on the most significant collapses, subsidence phenomena, and masonry repairs and cracks. The analysis identified the resonance frequency of the surface soft soil layer, linking it to the geological and geotechnical features. The findings consistently confirm the suggested

[31] Paschetto 1912, p. 113.
[32] Clemente *et al.* 1994.




8. HYPOTHESIS ON THE COLLAPSE DYNAMICS OF THE MASONRY STRUCTURE IN THE NORTHWEST FOR SEISMIC EVENTS (elaboration by L. Pecchioli and G. Cangi)

geological model, indicating no significant lateral variation in the Ostia Antica area amplification effects. Nonetheless, the observed seismic effects showed the earthquakes had varying epicenters and propagation directions. Detailed geomorphological reconstruction studies indicated a local fault line could trigger minor earthquakes.

After a thorough examination of the existing literature, it appears that there has been long-standing activity along a fault line running in a W-SW/E-NE direction at the town's northern boundary. In Pecchioli[33] and Marra[34], the authors propose a network of inferred faults running parallel or perpendicular to the coastline, as illustrated in *fig*. 9. One fault, labeled 'C' and trending SW-NE, has formed a half-graben, forcing the Tiber River to abruptly shift its course by about 90° from NNW-SSE to NNE-SSW. The collapse vectors in the case studies indicate the path of seismic waves but do not denote specific events. The results of the most recent seismic study in 2019 supported the idea of a primary S-SE direction, with secondary influences from N-NW and W-SW[35]. The greater distance from Ostia to the main Apennine seismic sources verified that local sources were responsible for the damage.

## 2. Environmental Monitoring System (2022)

The initial steps for conducting planned maintenance and analysing matching data and deformations involve understanding the monument's knowledge and environmental context. Creating a repeatable methodology can ensure the identification of structural damage and its progression. Implementing cyclical measures aids in precisely targeting criticality plans and establishing risk zones.

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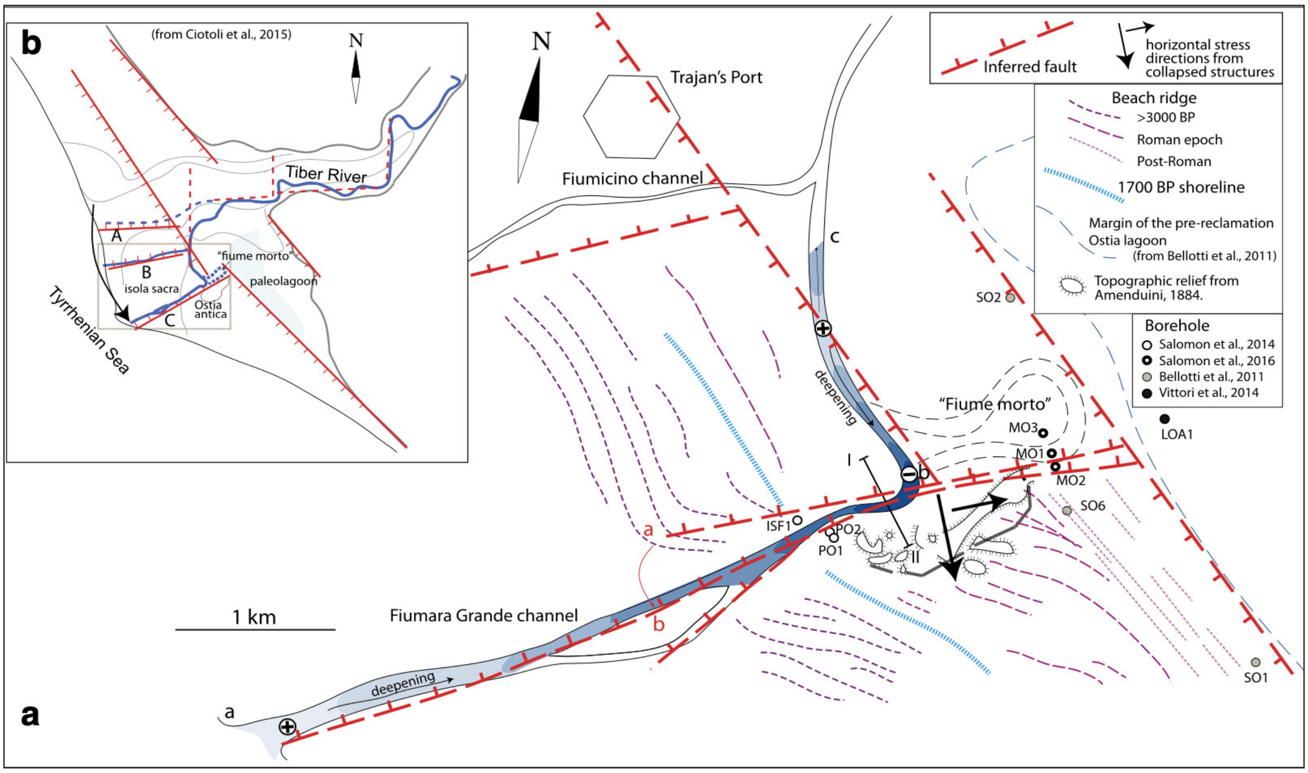
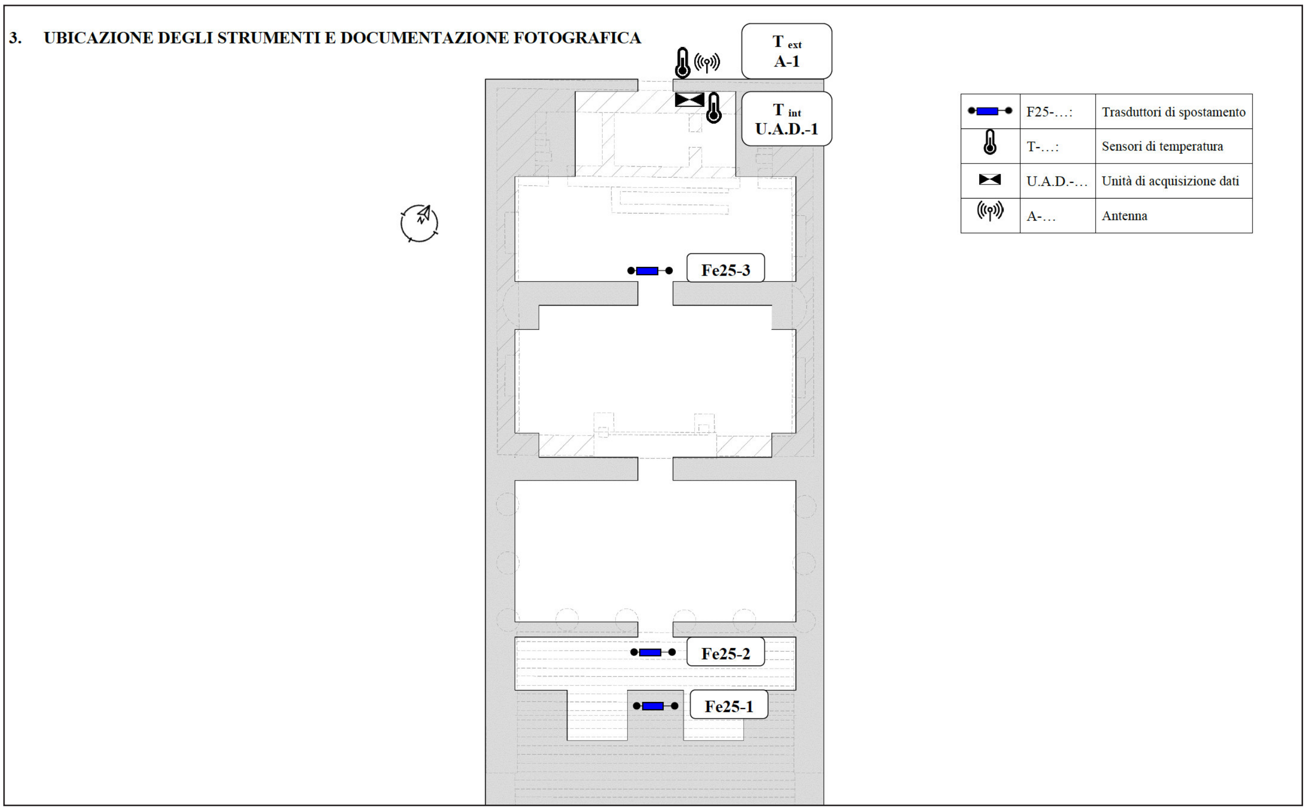
[33] Pecchioli *et al.* 2018.
[34] Marra *et al.* 2020.
[35] Measurements were redone in 2019 on new samples (Piccolo Mercato and the east and west Portici of Pio IX) to study the torsional effects on two pillars. The micro-zonation study indicates a soft soil layer with shear wave velocity ranging from 100 to 300 m/s. At depths of 35 to 40 meters, a weak interface with shear wave velocity above 500 m/s is observed. This velocity profile aligns with Marra *et al.*'s 2020 geological model based on borehole data. The minor impedance contrast between 35 to 40 meters indicates no significant amplification effects in the area.




9. A-B. STRUCTURAL-GEOMORPHOLOGICAL MAP OF THE INVESTIGATED AREA, SHOWING THE LOCATION OF THE INFERRED FAULTS (elaboration by Authors from MARRA *et al.* 2020)




10. *CAPITOLIUM* FLOOR PLAN: POSITIONING OF SENSORS (elaboration by C. Russo)

Implementing environmental monitoring has facilitated the gathering of valuable data, enhancing the analysis of interdisciplinary studies that might have remained unshared and underexplored. As noted in the introduction, after the 2016 earthquake, the Ministry requested a damage assessment of the *Capitolium*'s structural deformation. They had to choose between using only satellite data or a mix of satellite and ground sensor data, considering both structural and micro-climatic factors for sensor placement. The influence of soil characteristics and soil–structure interaction were the main issues relative to the stability. Environmental monitoring enables us to assess how the major crack in the vaulted ceiling behaves over the seasons. This information enhances the evaluation of conservation conditions, which considers the monument's exposure and helps define associated risks and vulnerability levels. Following the fragility criterion, we chose cases from diverse regions to cover the entire spectrum, prioritising those already reported with structural weaknesses. They monitored areas overlapped by satellite flights, as not all flights were relevant. Selection was also based on affected zones and available funds.

Consequently, the *Capitolium* was outfitted with real-time monitoring plugins, enabling data access from the platform for two years. This information will establish a database accessible to various archaeological park administrations. The automatic monitoring system comprised three displacement transducers to monitor crack opening and closing, two waterproof sensors for measuring indoor and outdoor ambient temperatures, a data acquisition unit, an ultra-narrow band modem for data transfer, and software for viewing and storing data on a web server platform (*fig.* 10).

The current monitoring method is versatile and compatible with other sensor technologies. It is desirable to introduce a vibrational measurement system based on positioning accelerometers on external masonries, which show significant crack patterns. As part of the Copernicus project, adopting sensor-based and remote sensing methods, like those in *Capitolium*, highlights an innovative approach to preserving cultural heritage. Similar to the Hyperion Project 3, the generated data will include flood monitoring maps, 3D asset models, and comprehensive evaluations of deterioration and material loss, significantly contributing to a preventive maintenance schedule on an urban scale.

### 2.1 Technical procedure

The automatic monitoring system, installed on 17 January 2022, consists of:

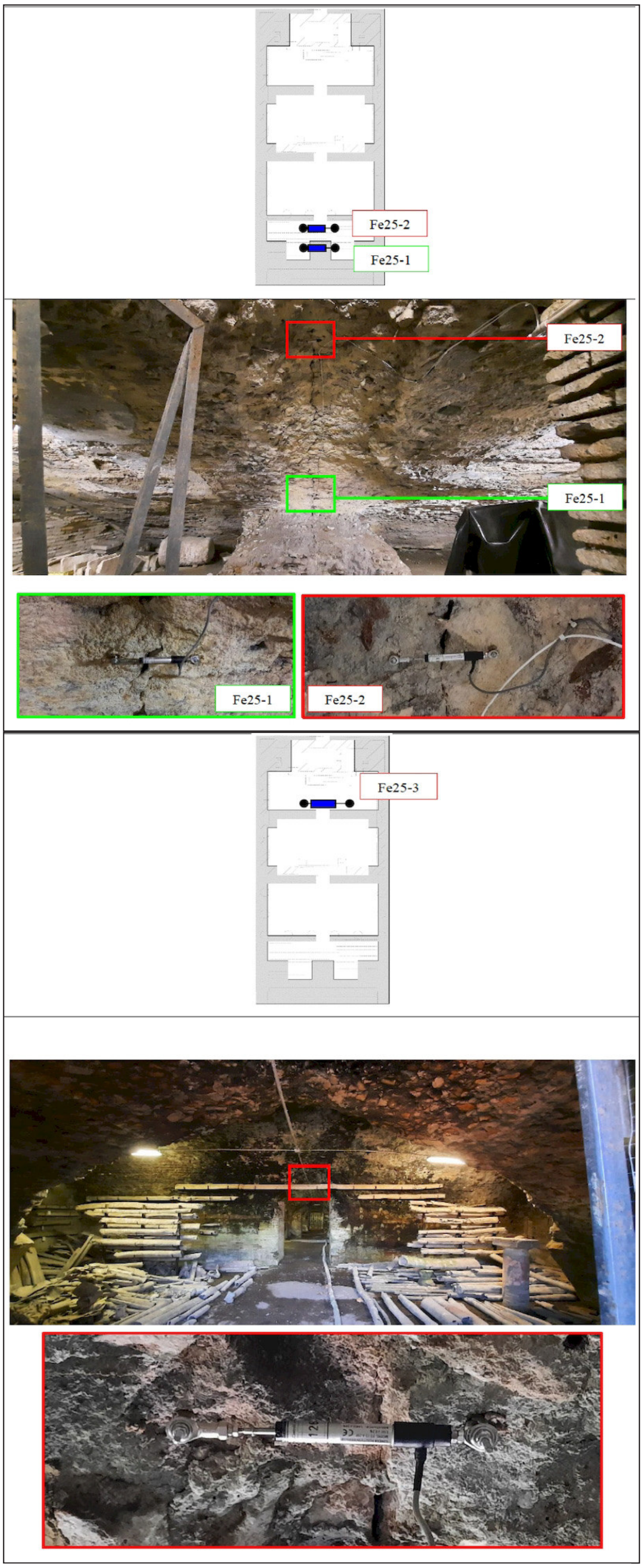
- n. 3 displacement transducers for controlling the opening/closing of the cracks;
- n. 2 sensors for measuring the internal and external ambient temperature;
- n. 1 data acquisition unit; - Ultra narrow band modem for data transfer;
- software for visualising and storing data on a web server platform.

The system acquires physical data from the instruments every two hours (12 daily acquisitions).

The acquisition system stores the data in internal memory and a cloud server accessible from the Internet. Thresholds have also been set on each channel. When they are exceeded, an email and a 'push' notification are sent to the job manager. Periodically, a remote check of the entire system's correct functioning is carried out. Finally, the data is processed and diagrammed using specific programs.

### 2.2 Data acquisition

The datalogger is an autonomous acquisition device suitable for unmanned remote data acquisition stations. The remote station performs measurements autonomously based on the provided programming and records data in its memory (Secure Digital card) until it is transferred to the user system. Afterward, the acquired data is simultaneously written into a file archived through a cloud storage service. The data acquisition system has been developed to provide considerable flexibility in the various types of measurements possible. The versatility of the input configuration allows




11. A. PLACEMENT OF LESION MONITORING SENSORS UNDER THE STAIRCASE; B. DETAIL ABOUT THE SENSOR TYPOLOGY (elaboration by C. Russo)

for the connection of sensors with diverse analog signal characteristics and several conductors. Programming using a smartphone with a Bluetooth connection makes it possible to define the measurement configuration for each sensor type. It is also possible to set a threshold level on each channel. When exceeded, an email is sent with the above-threshold values recorded.

The software also allows switching between electrical units (V, A, Ohm) and physical units (temperatures, forces, deformations, rotations, etc.).

### 2.3 Measurers of variations in cracks opening

The complexity of the geometrical characteristics, the nonlinear behavior of the material, and the ineffectiveness of the connection between vertical and horizontal elements defined the dynamic behavior of the structure. The podium's deep crack risk assessment required ongoing monitoring. New displacement sensors, designed for optimal performance in a compact form, have been installed. These sensors leverage 'Hybrid Track' technology—a high-resistivity conductive plastic film wound on a precision coil, which interacts with a high-precision metal contact. This setup guarantees excellent resolution, durability, and stability across varying humidity and temperature conditions. The sensor includes spherical joints at the ends, enabling precise alignment and movement along its axis. Data from the datalogger is stored in the cloud, accessible in real-time via FTP, and graphically displayed on the website: https://www.spc-engineering.it/Monitoraggi/OstiaAntica/ (last access December 20th, 2024).

The monitoring results after one year show how the basement fracture has a cyclical behavior, with phases returning to their initial state and a residual, narrower return pattern. Fluctuations influence the result at the groundwater level, and dynamic stress patterns are exacerbated by climate change (*fig*. 11, A-B). Regular inspections ensure structural integrity, mitigating any accessibility risks. These data are significant, especially with the increased rainfall and considerable temperature fluctuations.

## Conclusions

Remote sensing has proven to be valuable in monitoring damage and protecting cultural heritage. Methods for safeguarding archaeological sites and monitoring strategies help us understand their conservation status and environmental impact. Studying past disasters, conservation efforts, and case studies in Ostia Antica and the surrounding area also enhances the knowledge of historical chronology and local seismology. Disaster events have influenced, shaped, and refined construction techniques. When damage is associated with a specific disaster or the simultaneous occurrence of events, understanding its effects necessitates a multidisciplinary methodological approach that involves cross-referencing written sources, excavation findings, and analysing building systems, including repairs and reinforcements.

Identifying the dynamics and cyclicity of damage phenomena—such as flooding, erosion, subsidence, and even minor seismic events—continues, as seen in the case of the *Capitolium*, to enhance our chronological historical knowledge within a broader context. In our case, combining various monitoring investigations offers crucial insights into the environmental context within the Forum and serves as a benchmark for other damage case studies. Natural disasters have affected *Capitolium*, with fluctuations in groundwater levels and rainwater infiltration likely impacting its preservation. As a consequence, various reinforcements and repairs have revealed centuries-old instabilities. Cracks in the masonry and barrel vaulting indicate localised deformations and diminished material cohesion and resistance.

Detailed studies of carpentry repairs and structural mechanics are ongoing to assess damage related to cracks along the *Capitolium*. One type of hypothesized instability appears to be the kinematic mechanism of overturning the façade by dragging the top portion of a corner wedge (southwest). Laser scanner surveys and environmental monitoring are ongoing to minimise foundation displacement and address significant subsidence issues throughout the building.

Based on past disaster events and current detailed local tracking, it may be possible to approximate the potential impact on the *Capitolium*. An interdisciplinary approach is crucial for developing current maintenance and protection strategies and accessibility.

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