

Use of GPR for supporting structural interpretation of collapsed archaeological asset

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Abstract – This study presents an integrated methodological approach for investigating the collapsed vaulted structures of the Circus of Maxentius in Rome, combining non-destructive geophysical diagnostics with advanced digital survey techniques. Ground-penetrating radar (GPR), using dual frequency ground-coupled antennas (200/600 MHz), was employed to detect subsurface anomalies related to the collapse of the vault that once covered the ambulatory beneath the cavea. The GPR data revealed distinct reflections, interpreted as the intrados of dislocated vault segments, which were cross-validated through 3D photogrammetric modeling and visual analysis of exposed collapse sections. The integration of GPR results with high-resolution digital documentation enabled the reconstruction of buried architectural elements and offered critical insights into the monument's structural evolution and post-collapse stratigraphy. This approach supports archaeological interpretation and the development of accurate virtual reconstructions, contributing to the broader goal of sustainable heritage valorization through digital technologies.

Keywords: Preventive archaeology, Heritage Structural Assessment, Geophysical survey, GPR, Photogrammetry

I. INTRODUCTION

The Circus of Maxentius, one of the best-preserved examples of Roman circus architecture, forms part of the broader monumental complex of the Villa of Maxentius along the ancient Via Appia in Rome. Despite its apparent structural integrity, several portions of the monument, particularly within the ambulatory supporting the *cavea*, have undergone significant collapse, much of which

remains buried beneath sediment and vegetation.

This study aims to investigate these buried structural collapses through the application of non-invasive diagnostic tools, with a particular focus on ground-penetrating radar (GPR) techniques. By combining geophysical prospection with high-resolution digital survey data, the research seeks to reconstruct the spatial development and degradation processes affecting the vaulted corridors of the *cavea*.

The integration of GPR analysis with three-dimensional modeling and architectural interpretation allows for a deeper understanding of the mechanisms of collapse.

II. THE CASE STUDY: THE CIRCUS OF MAXENTIUS

The Circus of Maxentius, together with the remains of the Imperial Palace and the dynastic Mausoleum, surrounded by a porticus, forms part of the vast archaeological complex known as the Villa of Maxentius (Fig. 1).



Fig. 1 Aerial view of the archaeological Complex

Constructed in the early 4th century AD under Emperor Maxentius (306–312 AD), this monumental complex lies between the second and third mile of the ancient Appian

Way in Rome. The complex reflects both the ambitions of a short but architecturally impactful reign and the interaction between new constructions and a richly stratified pre-existing landscape.

Maxentius's architectural project significantly reshaped the area by incorporating, modifying, or removing pre-existing structures. The planning and development of the Villa complex were deeply influenced not only by these earlier remains, but also by the site's complex geomorphological characteristics (Fig. 2). The landscape is largely shaped by the ancient Capo di Bove lava flow, which has given rise to a system of alternating valleys and plateaus, contributing to the highly articulated topography of the Appian Park [1]. Among the most prominent of these features is the Valle della Caffarella, a deeply incised valley that has long influenced land use and construction strategies in the area.

The Circus is set within a natural valley, framed by two prominent elevations. To the north lies a tuffaceous hill, which hosts the remains of the Imperial Palace and extends toward the Mausoleum of Romulus, itself enclosed within a large rectangular precinct. To the south, another rise—formed by the extensive lava flows of the Latium Volcano—is dominated by the Mausoleum of Cecilia Metella. The valley that accommodates the Circus was historically crossed by the *Rivus Maior* [2].

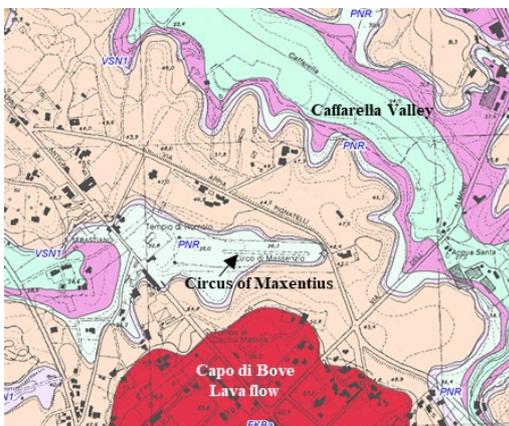


Fig. 2 – Geological framework of the area, (source: Geological chart of Rome Municipality)

In antiquity, the elevation difference between the northern hill and the valley was mitigated through the construction of an imperial corridor that physically and symbolically connected the Villa to the *Pulvinar*, the imperial viewing platform from which the emperor would have watched the games. The entire architectural complex was definitively attributed to Maxentius in 1825, when archaeologist Antonio Nibby discovered an inscription dedicated to the Divine Romulus, the emperor's son who died prematurely in 309 AD.

The Circus of Maxentius stands out as the only Roman circus whose entire perimeter is still preserved. Measuring

approximately 520 meters in length and 92 meters in width, it retains several remarkable architectural elements: the two corner towers, the retaining walls of the *cavea*, and the foundations of the *spina* and its two *metae*. Scholars generally agree that the complex was built in honor of Romulus and intended to host funeral games and commemorative ceremonies associated with his burial [3-4].

III. THE STRUCTURE

As previously noted, the Circus of Maxentius is unique in Rome for preserving its entire perimeter (Fig. 3). Nonetheless, the current state of preservation varies considerably across different sections of the structure. The most prominent remains are the two parallel perimeter walls that once delineated the *cavea*, or seating area, which extend longitudinally for the full length of the monument.



Fig. 3 – Aerial view of Cavea perimeter walls

The original vault of the *ambulacrum* - the corridor that supported the seating tiers - has largely collapsed. A notable exception exists in a short but significant section west of the *Tribunal* of the Judges, where traces of the extrados of the vault are still visible and can be examined *in situ*.

The southeastern sector of the *cavea* remains largely unexplored due to its burial beneath substantial soil deposits and dense vegetation. As a result, the degree of structural preservation in this area remains uncertain and requires further investigation, potentially through non-invasive survey methods.

The present analysis focuses on the northwestern sector of the *cavea*, specifically the stretch extending from the *carceres* - the starting gates for chariot races - to the eastern boundary of the *Pulvinar*. Within this area, the preservation of architectural features is comparatively in good condition, enabling a more detailed and accurate interpretation.

Beginning from the western end and extending for approximately 78 m, the vault of the *ambulacrum* is relatively well-preserved. A notable overhang remains, allowing for direct observation of the horizontal profile of the intrados. This structural configuration is particularly visible in the wall separating the vaulted corridor from the

distribution chamber located between the northwestern corner tower and the *carceres* (Fig. 4). Here, remnants of the vault begin at the high impost and continue for about 1.60 m with a flat profile, before transitioning into a fully ramping vault - a form that characterizes the rest of the structure.

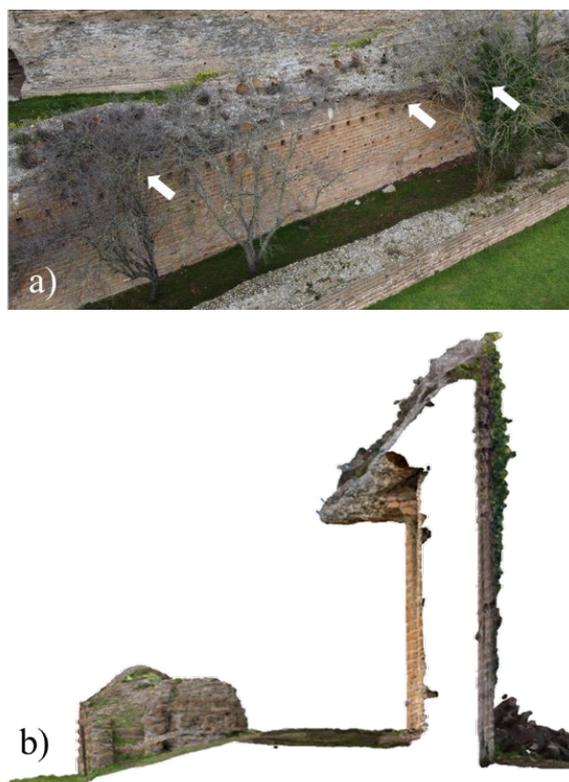


Fig. 4 –: a) aerial view of the cavea northern side and b) photogrammetry-based cross-section of the partially preserved intrados of the vaulted corridor

In contrast, the southern *ambulacrum* shows a different configuration: the vault here is entirely ramping from the impost, without the flat introductory segment observed in the northern part.

A particularly well-preserved portion of the vault reveals a narrow row of holes aligned just below the impost, interpreted as housing for wooden joists. The 20 cm of masonry separating these joist holes from the springing of the vault likely accommodated a sleeper beam, as evidenced by imprints still visible in the plaster and masonry.

IV. THE SURVEY METHODOLOGY

In order to achieve its objectives, the study adopted an interdisciplinary, integrated, and multi-sensor approach that combines non-invasive diagnostic techniques with advanced digital modeling tools. The methodology

involves the use of a variety of instruments and survey methods, each contributing to a comprehensive understanding of the structure through a sequential process of documentation, hypothesis formulation, and validation.

This methodology included both surface and subsurface data acquisition, aimed at documenting the preserved remains and detecting buried architectural features:

- a. Survey of the Emergent Structures: this involved the combined use of laser scanning, terrestrial photogrammetry, and low-altitude aerial photogrammetry via drone, allowing the generation of accurate three-dimensional models and orthophotos.
- b. Survey of the Hidden Structures: to investigate the buried portions of the *cavea*, a ground-penetrating radar (GPR) survey was carried out. This non-invasive technique enabled the detection of subsurface anomalies potentially related to collapsed vaults and other architectural elements that are no longer visible at ground level.

Ground-penetrating radar (GPR) is a well-known geophysical tool that works by emitting an electromagnetic field towards an inspected object and back-receiving the energy partially reflected as physical discontinuity are encountered by the EM waves. The analysis of the received reflections against their time of acquisition allows for the reconstruction of the physical properties of the inspected body, e.g., a layered natural soil [5]. According to its functioning principles, GPR has been widely and successfully applied in archaeological field [6] for retrieving or buried archaeological remains [7, 8], assessing the presence of voids or hidden rooms [9], evaluating structural defects [10], geometrical characterizations [11, 12].

In this study, was employed to gather information on structural elements that are no longer visible and therefore beyond the scope of conventional optical and digital surveying techniques [13, 14]. In particular, the aim was to investigate the collapsed vaulted structures of the *cavea*, which currently appear as a continuous soil embankment and lack any emergent architectural features.

The GPR survey was conducted using a pulsed ground-coupled system manufactured by IDS Georadar S.p.a. and equipped with dual-frequency antennas operating at central frequencies of 200 MHz and 600 MHz. The adopted acquisition parameters are reported in Tab. 1.

Tab. 1 GPR survey acquisition parameters

Central Frequency	200/600 MHz
Time window	80 ns
Horiz. resolution	0.044 m
Samples	512

This configuration was selected to ensure both adequate penetration depth and sufficient resolution, enabling the detection of sub-surface anomalies associated with collapsed architectural components.

Data acquisition was carried out by towing the radar system directly across the area of interest from the arena to the outer wall of the *cavea*, as depicted in Fig. 5.



Fig. 5 – GPR data acquisition

Various GPR scans were acquired with survey lines oriented to maximize coverage and spatial correlation with the standing remains (Fig. 6). In particular, the space interval between subsequent acquisition was set as 10 m approximately, as in the figure.

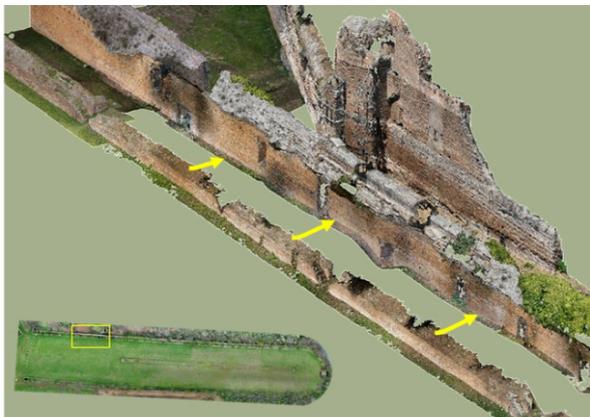


Fig. 6 GPR survey configuration in the assessed area

V. THE RESULTS

The interpretation of the GPR data, particularly when integrated with the outcomes of the digital survey, proved highly informative. The results made it possible to infer the geometry and spatial extent of the collapsed vaults, despite their current burial beneath fill material. In several instances, the radar reflections exhibited characteristics consistent with the presence of voids or changes in soil compaction, likely corresponding to the original volume and profile of the vaulted structures.

An example of 200 MHz EM response is shown in Fig.

7a. Particularly, a deep clear and curve-shaped reflection is observed between 1 m and 3.5 m of acquisition distance at a depth ranging between 2.5 m and 2 m, approximately. A second deep reflection, flatter and with different inclination, is observed between 3.5 m and 5 m of distance and between depth of 2 m and 1.5 m. These reflections can reasonably be interpreted as the intrados of two separate blocks of the collapsed *cavea* vault that, while collapsing, have rotated up to assume the position observed in the GPR scans. The different shape of intrados between the blocks can be explained thanks to the geometrical features observed in the preserved parts of the

This interpretation is also supported by a visual analysis conducted on the passages between the inner and outer part of the circus that, occasionally, expose the profile of collapses showing similar positions of the vault blocks (Fig. 7b).

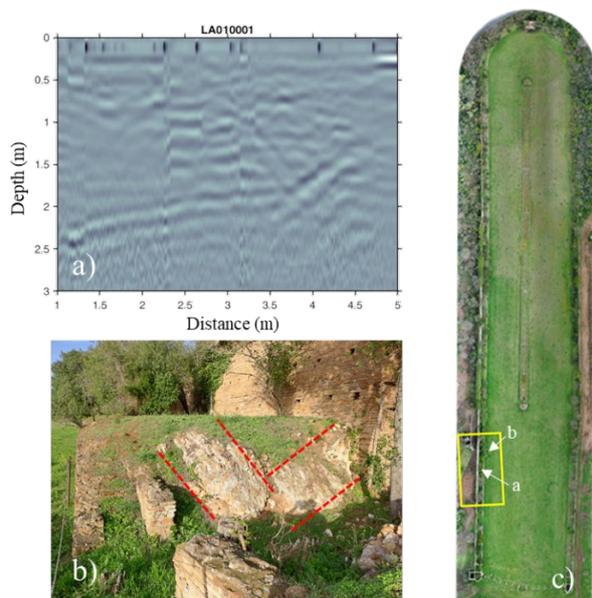


Fig. 7 a) a processed 200 MHz radargram, b) a visual analysis of exposed collapses located nearby, c) plan view of the position of radargram and visual analysis across the Circus.

A superior line of reflection with depth ranging between 2 m and 1 m in the direction of the scan, are found to comply with the thickness of the vault expected by archaeological analysis. This non-invasive geophysical investigation played a critical role in complementing the 3D digital documentation, allowing the reconstruction of portions of the structure that have otherwise been lost. The integration of GPR and digital survey data thus provides a more complete and nuanced understanding of the Circus's architectural evolution and post-collapse stratigraphy, an example of which is reported in Fig. 8 showing a reasonable reconstruction of the northern side of the *cavea*.



Fig. 8 – reconstruction of the cavea in the norther side of the Circus, courtesy of Drs. Dario Nepi and Daniele Rose.

VI. CONCLUSIONS

This study reports on the integration of various non-destructive survey methods and, especially, GPR for supporting the historical interpretation of archaeological asset being partially still buried.

More in detail, multi-frequency GPR tests have been carried out by towing a coupled antenna from inner to outer wall of the *cavea*, currently presenting as an embankment.

The outcomes of the GPR tests have highlighted the presence of two main objects showing regular reflections that can be reasonably interpreted as the intrados of collapsed blocks of the vaulted *cavea*. The depth of burial, the geometrical shape and the thickness of the object are found to comply with archaeological knowledge on the *cavea*.

The results of the surveys have confirmed the historical interpretation of the monument, driving the three-dimensional reconstruction. This is a key point in ensuring both the archaeological and structural reliability of the virtual reconstructions, which are fundamental tools not only to a deeper understanding of the structural and functional features of the historical building, but also for valorisation purposes, indeed allowing for virtual sight of the ancient aspect of the monument by in-presence and remote visitors.

VII. ACKNOWLEDGMENTS

The study was carried out in the framework of BIMHERIT research project, funded by DTC Lazio. Doc. E. M. Loreti - Sovrintendenza Capitolina ai Beni Culturali, responsible of the Villa di Massenzio archaeological site in Rome, is kindly acknowledged. Authors acknowledge Dr. Dario Rose and Daniele Nepi for works applied on 3D reconstruction and historical interpretation.

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