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Roman stone masonry walls: the application of Ground Penetrating Radar to ancient structures

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Abstract. An investigation on estimating Roman stone masonry wall thickness using non-invasive Ground Penetrating Radar (GPR) and Light Detection and Ranging (LiDAR) technology is presented in this paper. Historical building conservation and structural evaluation require correct wall thickness measurements. The methodology encapsulates data collection, signal processing, and interpretation techniques, including the use of local frequency attributes tailored for historical masonry structures. The main perimeter wall at the Circus of Maxentius, Rome, Italy, is used as the case study. The results indicate that GPR is capable of accurately estimating the thickness of Roman stone masonry walls. By conducting a comparative analysis against a wall section with a known thickness, it has been demonstrated that GPR is a dependable and precise method for conducting archaeological and architectural research. This study highlights the potential of using GPR attributes as a non-destructive investigative methodology in the field of heritage preservation. Future research includes extracting and improving further attributes and applying this approach to other historical structures.

1 Introduction

Understanding historical structures' architectural and structural integrity is essential to cultural heritage protection. Accurate wall thickness measurements can reveal construction methods, structural integrity, and restoration needs [1]. Coring through the wall or access to both sides are necessary for direct measurements. Coring and drilling to measure wall thickness can destroy old structures irreparably, as well as being time-consuming, and exhausting, especially in very hot or cold weather conditions. Thus, non-destructive methods that provide precise measurements without damaging the structure are in demand.

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Ground Penetrating Radar (GPR) is an indirect geophysical technique that, by transmitting high-frequency electromagnetic waves into the studied area and evaluating the reflected waves from anomalies and boundaries, generates a map of the internal characteristics of the medium. GPR is a well-known non-invasive technique that has been used to estimate thickness of various structures such as ice and glaciers [2, 3], asphalt [4], and pavements [5].

This technique can examine ancient walls without a physical interference, and provide extensive information about interior structures, cracks, and voids or deterioration [6, 7].

In this paper, GPR is utilised to estimate the thickness of Roman stone masonry building walls. We use a known thickness wall as a case example to demonstrate that extracting the local frequency of GPR data can provide precise and reliable estimations. Historical masonry presents unique physical obstacles and logistic constraints; hence the study uses a rigorous data gathering, signal processing, and interpretation methodology. The local frequency attribute is compared to established methods to verify its accuracy and reliability.

2 Statement of the Problem

An accurate, non-invasive, and efficient approach to evaluate the thickness of historical stone masonry building walls is urgently needed. GPR seems promising, but its use in this context has got limitations in terms of providing an accurate data interpretation in heterogeneous materials.

As of now, the current GPR processing methodologies suffer to provide a clear understanding of the problem. This problem must be solved to improve upon the current non-invasive heritage conservation, ancient building preservation and structural assessment programs.

3 Aim and Objectives

This study aims to develop and validate a GPR-based data analysis approach to enhance the accuracy in measuring the thickness of Roman stone masonry walls.

To achieve this aim, the following objectives have been identified: (i) to develop a standardised methodology for GPR data acquisition, processing, and interpretation specific to ancient walls; (ii) to implement dedicated signal processing techniques that can enhance the clarity and the accuracy of the GPR data interpretation; (iii) to compare the GPR results with measurements obtained from a known thickness wall and validate their accuracy; and (iv) to suggest future research directions to improve the application of GPR in this field.

4 Methodology

Two processing methodologies, i.e., Framework I and Framework II (Figure 1), have been utilised to process the data. A comparative analysis and interpretation of the respective outcomes has been subsequently performed.

In Framework I, basic and advanced processing steps including time-zero correction, Dewow filter, background removal, a gain (inverse amplitude decay), non-local filter and topographic correction were applied to enhance the signal clarity. The time-zero correction was employed to accurately position the A-scans and, as a result, the subsurface targets at their precise depth location [8]. This is particularly effective for targets at shallow depths. Dewow is employed to mitigate the impact of low-frequency undesired reflections superimposed on high-frequency reflections in the GPR sections [9]. Background removal is employed to eliminate direct air and ground waves. The gain is used to offset the decrease in power of the electromagnetic waves as they penetrate to depth. Non-local filter is used for the attenuation of random noise in the GPR sections [9]. Finally, the acquisition of Light Detection and Ranging (LiDAR) data has allowed to position the processed GPR traces in their correct location by applying topographic correction.

In Framework II, only time-zero correction and Dewow filter were applied to preserve the frequency content of signals, and the local frequency attribute was extracted afterwards. Similar to Framework I, LiDAR acquisition allowed to relocate the processed GPR traces through topographic correction.

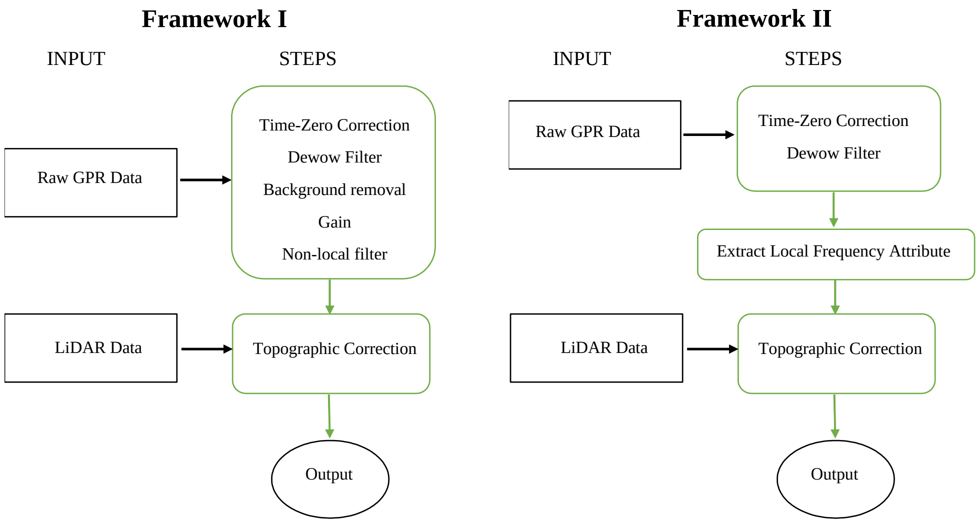

Fig. 1. The two Frameworks relative to the GPR processing pipelines presented in this study. Model inputs include the raw data files and the LiDAR data. Processing steps are summarised in the text.

GPR attributes refer to features that are extracted from the measured data either before or after the processing, with the aim of enhancing interpretation.

A vast number of characteristics have been retrieved in seismic exploration, with certain specific ones being highly significant in the analysis of data [10]. The local frequency is one of the known seismic attributes that measures the signal characteristics not instantaneously, at each data point, but in a local neighbourhood around the point. Conversely, the instantaneous frequency is notoriously noisy and may lead to unphysical values such as negative frequencies [11]. The instantaneous frequency, $\omega(t)$, is defined as the rate of change of the instantaneous phase, $\emptyset'(t)$, over time:

$$\omega(t)=\emptyset'(t) = \frac{f(t)h'(t)-f'(t)h(t)}{f'(t)+h'(t)} \qquad (1)$$

Where $f(t)$ and $h(t)$ are the real trace and the Hilbert transform of the real trace, respectively. The inversion scheme of the local frequency is defined as follows:

$$\boldsymbol{W}_{loc} = [\lambda^2 \boldsymbol{I} + \boldsymbol{S}(\boldsymbol{D} - \lambda^2 \boldsymbol{I})]^{-1} \boldsymbol{Sn} \qquad (2)$$

Where $\boldsymbol{S}$ is a smoothing (shaping) operator, $\boldsymbol{D}$ is a diagonal operator made from the denominator of equation 1, $\boldsymbol{n}$ represents the numerator in Equation (1), $\boldsymbol{I}$ stands for the identity operator, and λ is a scaling factor. Using the scaling factor preserves the physical dimensionality and speeds up the iterative process of the inversion. $\boldsymbol{D}$'s least-squares norm is a suitable option for λ.

An in-depth description of the mathematics and concepts related to this attribute, can be found in [11]. This powerful tool is used to enhance the resolution and the interpretability of seismic data, aiding for a more precise geological and reservoir characterisation.

To test the two proposed signal processing frameworks, the algorithm was initially implemented on a test wall section that allowed access to both sides and, hence, a precise thickness measurement through LiDAR technology. After confirming the accuracy of the outcomes, the tested algorithm has been subsequently applied to another wall section, where the thickness was not known. It is worthy of mention that estimating the electromagnetic wave velocity in the studied environment to transform time sections into depth sections is a fundamental issue in GPR science. The velocity of the electromagnetic wave can be determined by collecting data with several transmitters and receivers, which is a time-consuming process. This article estimates the electromagnetic wave velocity at 11 cm/ns based on the known wall thickness.

5 Test Site and Equipment

A GPR survey was conducted at the Circus of Maxentius, Rome, Italy. This building, along with the structures of the Palace and the dynastic Mausoleum, constitutes the archaeological complex of the Villa of Maxentius. The complex dates to the 4th century AD, and it is situated between the 2nd and 3rd mile of the ancient Appian Way (Figure 2) [12, 13]. The area is characterised by a preexisting architectural context that was diversely integrated or dismantled by the Maxentius's project. The late antique layout was influenced by the preexisting structures as well as by a complex site geomorphology, also during the planning phase.

The Circus, 520 m long and 92 m wide, is the only one of its kind in Rome with a fully preserved perimeter. Nowadays, the visible remains include the imposing remains of the two corner towers, the retaining walls of the stairs and all the foundations of the spina and the two metae. The building was topographically connected to the Villa through the Imperial Pulvinar, the structure where the Emperor was in attendance for the games. At present, the raise in levels occurring over the centuries and following site abandonment affects having an objective perception of the actual wall profile at several locations. The scope of the study presented in this paper is therefore aligned with the actual needs of this monument [14, 15].

Measurements were carried out using a dual-frequency constant offset ground-coupled GPR system manufactured by IDS GeoRadar (Part of Hexagon) (Figure 3). The system uses transmitting and receiving antennas of a shielded type, which can operate at central

Fig. 2. Aerial view of the Villa of Maxentius, Rome, Italy.

Fig. 3. GPR data collection on the perimeter stone masonry wall at the Circus of Maxentius.

frequencies of 200 and 600 Mhz. For this study, only the 600 MHz central frequency was used. GPR data were collected as vertical transects on the wall sections from bottom to top (Figure 3), using a trace spacing and a sampling interval of 0.2 cm and 0.12 ns, respectively.

6 Results and Discussion

Figure 4 presents the measurement results obtained with LiDAR and GPR. The thickness profile of the test wall was precisely determined through a continuous LiDAR scanning of both sides (Figure 4A).

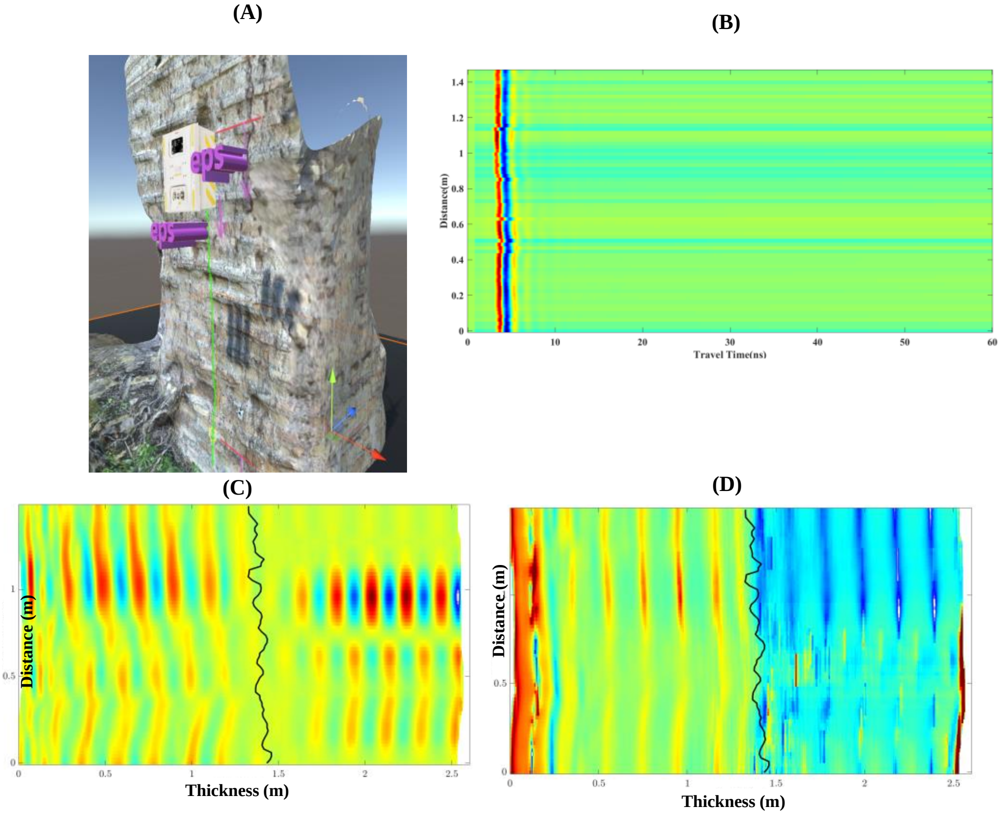

Fig. 4. Test wall with a known thickness: (A) LiDAR digital model, (B) GPR raw data, (C) processed GPR data (result of Framework I), and (D) GPR data with local frequency attribute (result of Framework II).

The average thickness profile from LiDAR turned back to be 140 cm. This information was then utilised to assess the goodness of the results from the application of the two proposed GPR-based frameworks (Figure 1). The end position and shape of the wall is indicated with a black solid line, and it is over imposed in the extracted GPR results (Fig. **4**C and 4D). The GPR scanning side of the wall in Figures 4B-D is located on the left-hand side of the plots. While it was not possible to extract a net interface between the wall and the air layer from the application of Framework I, a clearer interface could be identified by Framework II, with an average thickness value of 137 cm.

Similarly, the application of Framework I to the wall section with unknown thickness (Figure 5A and 5B), did not allow for a clear identification of the interface (Figure 5C). The implementation of Framework II clearly defined the wall/air layer interface (Figure 5D), and returned an average thickness value of 136 cm, with absolute minimum and maximum values of 135 cm and 139 cm, respectively.

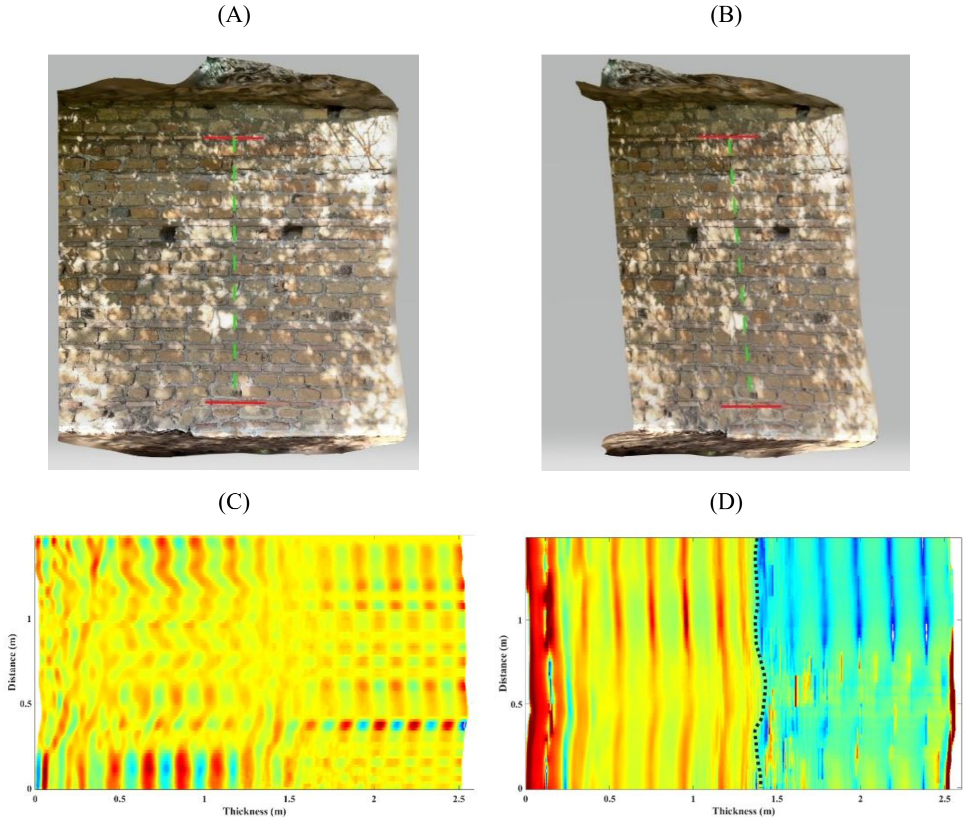

Fig. 5. Investigated wall section with unknown thickness: (A) LiDAR digital model, front view. Red lines set the terminal bottom and upper sections of the GPR scanning vertical transect (dashed green line), (B) LiDAR digital model, side perspective view, (C) GPR data from the implementation of Framework I, (D) GPR data from the implementation of Framework II; the dashed black line indicates the estimated wall-air layer interface.

7 Conclusions

This work has proven the potential of Ground Penetrating Radar (GPR) as a non-invasive and accurate method for collecting information on the thickness of Roman stone masonry walls through the application of the local frequency attribute. The use of enhanced data processing methods has returned viable outcomes that improved upon the clarity and the interpretability of the GPR findings.

With reference to the specific case study carried out at the perimeter wall of the Circus of Maxentius in Rome, Italy, a conventional GPR processing methodology (i.e., Framework I in Figure 1) and a GPR attribute-based methodology (i.e., Framework II in Figure 1) have been proposed and the outcomes compared with each other. Both Frameworks use raw GPR data and Light And Detection Ranging (LiDAR) data as input information.

The GPR attribute-based methodology, based on the local frequency attribute, has facilitated a clearer understanding of the thickness of the perimeter wall at the investigated section, which was not easily accessible and could not be measured directly on site. The proposed approach applied on a test wall of known thickness returned an average thickness value for the LiDAR and the enhanced GPR-based methodology (Framework II) of 140cm and 137 cm, respectively. No clear interface could be determined using the more conventional signal processing approach of Framework I. Similar outcomes were observed for the wall with unknown thickness, with no interface detection from Framework I, and a clearer interface provided by Framework II (average thickness value of 136 cm).

In general, the enhanced processing method proposed in this study ensures a higher level of knowledge of the non-visible geometric properties of masonry walls in historical buildings. This is crucial to achieve a more comprehensive understanding of structural, operational and construction-related functions of historical buildings. The implementation of the proposed methodology can support archaeologists, conservationists and professionals in the sector to make more informed, rapid and upgradable decisions in preserving cultural heritage assets.

Additional research can task itself on combining GPR with LiDAR technology to create detailed three-dimensional depictions of historical buildings. Moreover, additional studies could be carried out to extract and develop other attributes as processing tools to improve the information level in the interpretation of GPR data.

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