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CHARACTERIZATION OF A PRE-TRAJAN WALL STRUCTURE BY INTEGRATED GEOPHYSICAL METHODS

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ABSTRACT

The aim of this study is the characterization of a pre-Trajan wall structure decorated with mosaics and located below the Cryptoporticus of the “Baths of Trajan” complex in Rome. The surveyed wall is 15 m large and 0.9 m wide, with an height ranging from 3 to 5 m.

Ground Penetrating Radar (GPR) and Seismic Refraction Tomography profiles were performed on the wall for reconstructing its inner geometry as well as characterizing its building materials, with the additional purposes of mapping fractures and evaluating seismic velocities of materials, to give safety indications before restarting the excavation.

The wall was surveyed with horizontal and vertical massive GPR profiles and with two seismic lines.

Both the seismic lines and the GPR profiles are able to detect the discontinuity between the two different materials forming the wall, confirming the consistency of the joint interpretation of the two different non-invasive techniques. Moreover they allowed us to locate weak materials and fractures. These results will be used for planning a safety project for the future archaeological excavations.

We demonstrate that this approach constitutes an important tool for the characterization of the current status of an archaeological wall.

KEYWORDS : *pre-Trajan wall, Seismic Tomography, Ground Penetrating Radar, mapping fractures*

INTRODUCTION

Over the past few decades, non-invasive geophysical techniques have been successfully applied for the safety assessment of ancient structures to support forthcoming archaeological investigations. Despite the large amount of applications, a unified approach for data acquisition and monitoring is still lacking, because the peculiar characteristics of each archaeological site prevent from using a standardized procedure.

GPR has been widely used for archaeological prospection in recent years, since it can rapidly provide important information about the location and the geometry of buried bodies, without any damage to the structure under investigation; in fact, GPR has been successfully applied to detect and characterize ancient structures (e.g. Orlando and Slob 2009; Cataldo et al. 2012) and to locate Roman buildings (e.g. Neubauer et al. 2002; Piro et al. 2003), confirming the capability of the GPR method for detecting buried structures, cavities and hidden objects in the shallow subsurface or within ancient buildings to assess the current state of the structure and give safety indications to the archaeologists.

On the other hand, seismic tomography has been used to reconstruct an high-resolution image of structures and ancient buildings (e.g. Cardarelli and de Nardis 2001; Polymenakos et al. 2005) with the primary aim to assess the elastic rock properties.

In the scientific literature on the subject, only a few studies concerned the application of multi-method non-destructive testing for monitoring cultural heritage, encompassing GPR and seismic

tomography (e.g. Orlando and Renzi 2013; Perez-Gracia et al. 2013) or GPR and Electrical Resistivity Tomography (e.g. Grangeia et al. 2011).

This study is focused on an integrated application of geophysical methods (GPR and seismic refraction and transmission tomography) to characterize an archaeological wall of pre-Trajan age. The investigated wall is located under the Cryptoporticus of the “Baths of Trajan” at the Colle Oppio (Rome historical centre), near the Domus Aurea complex. It was discovered during the latest archaeological campaign (2012) by the Sovrintendenza Comunale ai Beni Architettonici (City of Rome – Authority of Cultural Heritage). The wall is 15 m large and 0.9 m wide, with an height ranging from 3 to 5 m, and it is partially decorated with mosaics, probably representing the God Apollo and the Muses (Fig. 1).

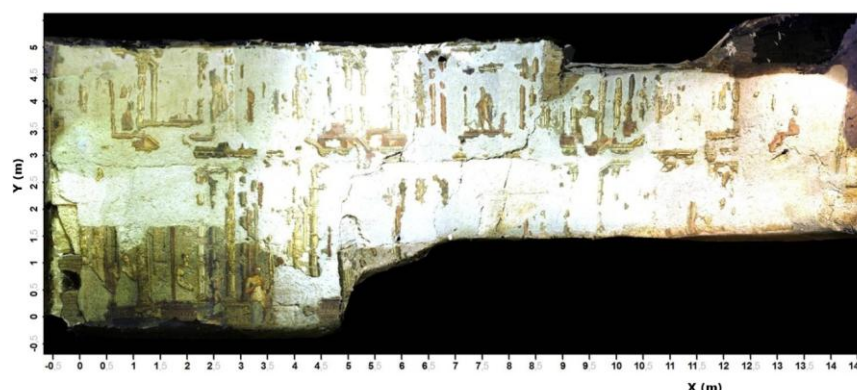


Figure 1 : Rectified image of the pre-Trajan wall.

This wall is probably only a part of a 300 m² Roman *domus*, that is expected to be fully excavated in a future archaeological campaign. Hence, the Authority needs to assess the integrity of the wall to avoid any possible collapse during the planned future excavations. In light of this, it was also crucial to map the materials constituting the wall (travertine and bricks), because they are largely covered by plaster and mosaics (Fig. 1). In particular, a preliminary visual survey indicates that probably the bricks are superimposed to the travertine that is located mainly in the central part of the wall (y=1.5-3.0 m in Fig. 1).

The proposed investigation procedure involves the sequential application of GPR and seismic tomography. These techniques are low-budget, rapid and their integrated application can provide important information about the composition and the geometry of the wall, an extensive mapping of fractures and anomalies embedded within the wall and eventually the correlation between different physical and mechanical parameters.

1 DATA ACQUISITION AND PROCESSING

A preliminary GPR screening involved three different frequencies (600 MHz, 900 MHz and 2 GHz) with different layouts and materials used for the protection of the surface mosaics. We chose the 900 MHz frequency for the whole investigation (Fig.2, left), as it was found to have, for this application, the best trade-off between resolution and depth of investigation.

The surface of the wall was divided into 50x300 cm geo-referenced panels (Fig. 2, right), made by plywood and polystyrene, deployed above the wall to preserve the integrity of the mosaics, although reducing the signal penetration. Vertical and horizontal GPR profiles spaced 20 cm apart were acquired (Fig. 3) according to this layout.

In addition, two seismic profiles were acquired on the wall (Fig. 3): a vertical profile for a seismic refraction tomography (S1) and a seismic transmission tomography in the upper part of the wall (S2).



Figure 2 : 900 MHz antenna (left) and plywood panels (right).

The S1 profile (Fig.4, left) is 3 m long and consists of 23 sensors spaced 13 cm apart. The sensors are piezo-electric accelerometers with a cutoff frequency of 4 kHz. In order to avoid any damage to the wall and to enhance the signal-to-noise ratio, the contact between wall and sensors was implemented by using sticking plasters and silicone. The profile was collected using 13 shot points (operating a 2 kg hammer source) with a sample rate of 31.5 micro-s.

For the S2 profile we employed the same instrumentation with 23 sensors spaced 15 cm apart, while the 19 shot points are located on the investigated side of the wall and the receivers on the opposite part (Fig.4, right).

The parameters employed for data acquisition are reported in Table 1.

Table 1 : Acquisition details for the GPR and seismic investigations.

Survey	Acquisition details
Ground Penetrating Radar	<i>Spacing:</i> 20 cm (<i>x</i> and <i>y</i> directions)
	<i>Covering material:</i> plywood and polystyrene
	<i>Device:</i> IDS 900MHz antenna
Seismic tomography	<i>Receivers:</i> 23 piezo-electric sensors 13 cm (S1) and 15cm (S2) spaced, with cut-off frequency 4kHz
	<i>Shots:</i> 12 (L1) and 19 (L2) shot points
	<i>Device:</i> 2 Seismographs Geode Geometrics

For each shot gather and for both acquisition geometry (S1 and S2), the first arrivals were manually picked and the traveltimes computed as the difference between the shot instant and the first breaks of the wave. Then, seismic tomography was performed employing the linear traveltime interpolation (LTI) method for ray-tracing (Asakawa and Kawanaka 1993; Cardarelli and de Nardis 2001) and the iterative biconjugate gradient algorithm for traveltime inversion (Cardarelli and Cerreto 2002).

2 RESULTS AND DISCUSSION

Firstly, GPR data processing (time zero correction, vertical band pass filter (200-1500 MHz), an horizontal band pass filter, linear gain and migration) was tuned to improve the signal-to-noise ratio and make easier the data interpretation. The time-depth conversion was obtained using a velocity of 9 cm/ns, evaluated by fitting the diffractions with the theoretical hyperbola. The interpretation is based on the results derived from both the horizontal and vertical profiles and from the horizontal sections at different times (*time slices*).

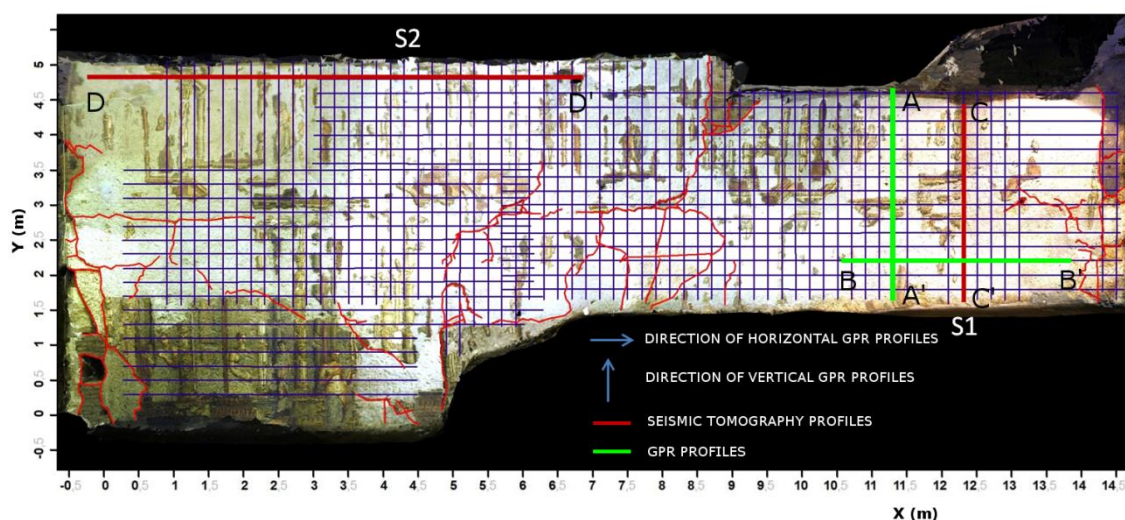


Figure 3 : Location of GPR and seismic profiles.



Figure 4 : S1 (left) and S2 (right) seismic profiles.

An example of unmigrated vertical and horizontal profiles (located as indicated in Fig. 3) is shown in Fig. 5. The vertical profile (Fig. 5a) is situated along the transition zone between the bricks and the travertine while the horizontal profile (Fig. 5b) is acquired entirely on the travertine. The GPR profiles show different signatures of the two materials in terms of signal attenuation and intensity of scattering. In fact, although the GPR investigates the whole thickness of the wall (90 cm) in the travertine part, only a depth of 40 cm is visible in the bricks (Figs. 5a and 5b), due to the higher signal attenuation.

When the analysis is performed on the time-slices, we can retrieve additional information about the composition of the wall and the location of anomalies and fractures.

More specifically, considering the time-slice computed over the entire wall (90 cm) using true amplitude vertical profiles without the application of a gain (Fig. 6a), we detected an high energy zone situated in the lower part of the wall (travertine blocks) and a low energy zone in the higher part. Furthermore, since the scattering energy varies significantly passing from the left part of the slice ($x=0-4$ m), to the right part ($x = 4-12$ m), the travertine blocks exhibit different properties probably related to either composition or quality.

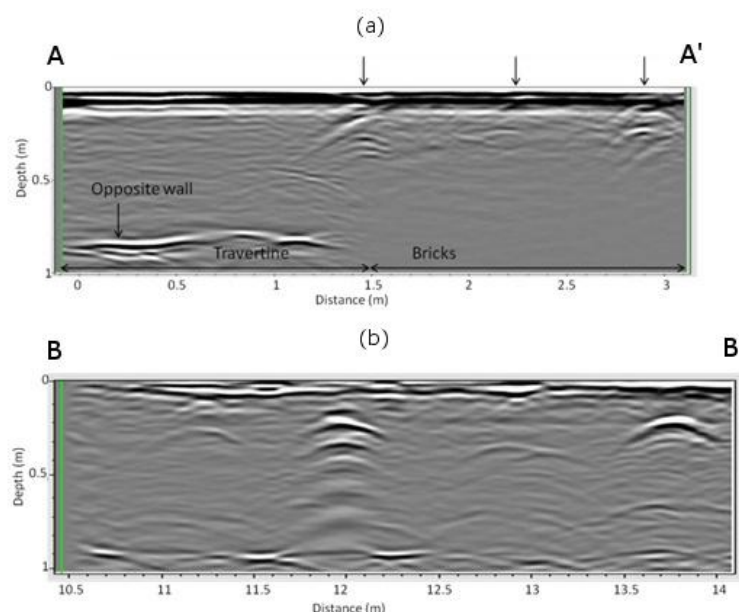


Figure 5 : A-A' (a) and B-B' (b) GPR profiles (see Fig.3 for the location of profiles)

The shallower time-slices ($z=20$ and 40 cm, Figs. 6b and 6c), calculated using the horizontal profiles, show different anomalies both in the travertine and in the bricks, mainly located on two main rows ($y=2$ and 3 m) and probably related to construction elements embedded within the structure.

Starting from this extensive GPR mapping, the seismic tomography is employed for retrieving the physical and mechanical parameters of the investigated structure.

The inverted section of the seismic tomography S1 (Fig. 7b) detected two main zones in the z -direction, according to the respective GPR profile (Fig. 7a): the shallower (up to 40 cm) having a P-wave velocity ranging from 400 to 700 m/s and a maximum depth of 50 cm and the deeper with a P-wave velocity of about 800 - 1000 m/s. We underline that where ray coverage is poor or absent the algorithm colours the pixel in white. In addition to this, the P-wave velocity decreases passing from travertine to bricks ($x=1.4$ - 1.5 m in Fig. 7b). Therefore, the investigated wall exhibits a high degree of heterogeneity not only in the x - and y -directions but also in depth, where the shallower part exhibits lower P-wave velocities when compared to those referable to deeper zones.

The inverted model of the seismic tomography S2 (Fig. 8) provides a P-wave velocity distribution that confirms the heterogeneity of the materials constituting the wall. In particular, the high velocity zones (800 - 1200 m/s) are located near the wall surfaces, whereas the inner part of the wall is characterized by lower velocities (400 - 700 m/s).

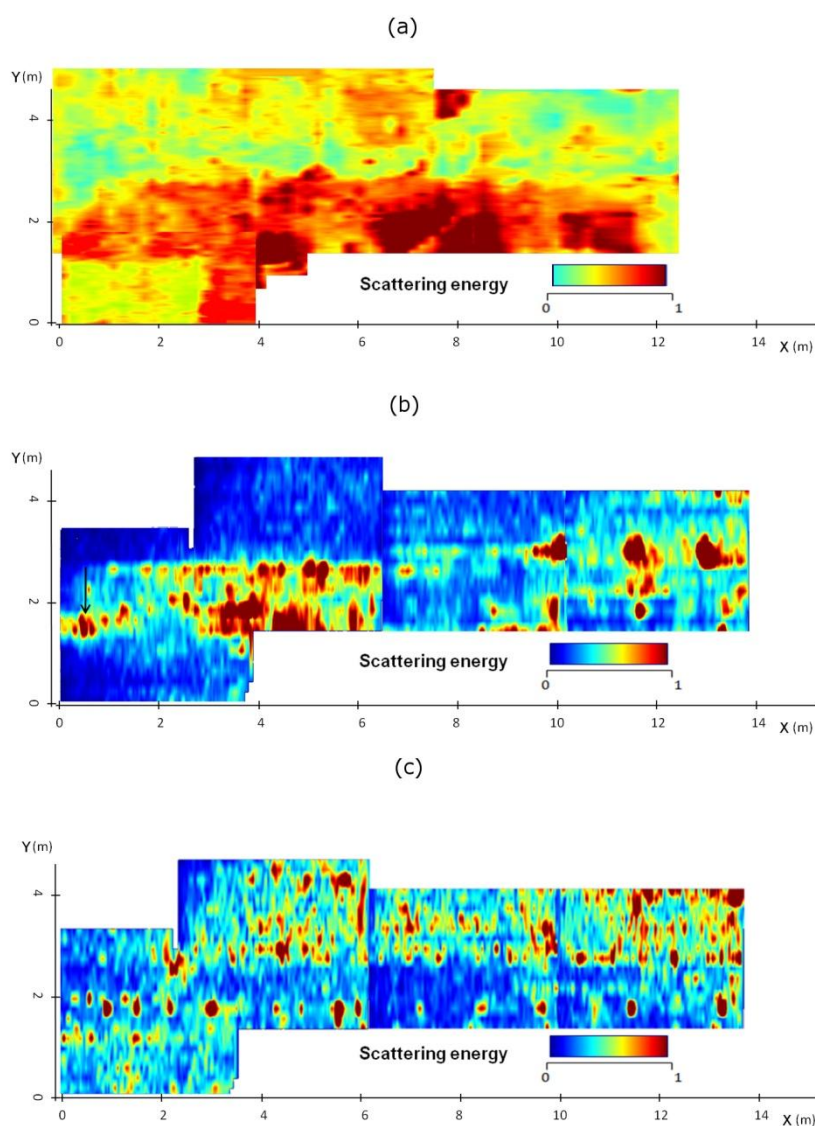


Figure 6 : Time-slices calculated considering the vertical profiles for a significant thickness of 90 cm and at $z=50$ cm without using a gain (a), considering the horizontal profiles for a significant thickness of 20 cm and at $z=40$ cm with gain (b) and considering the horizontal profiles for a significant thickness of 20 cm and at $z=20$ cm with gain (c).

Since this seismic line is located entirely on the bricks, the differences in the velocity distribution (and consequently in the composition) can be attributed to the peculiar construction method adopted for this structure. In fact, this wall was built using the *opus caementicium* technique, with bricks in the outer part of the structure and a mixture of aggregate, water and pozzolana, having poor mechanic characteristics, in the inner part.

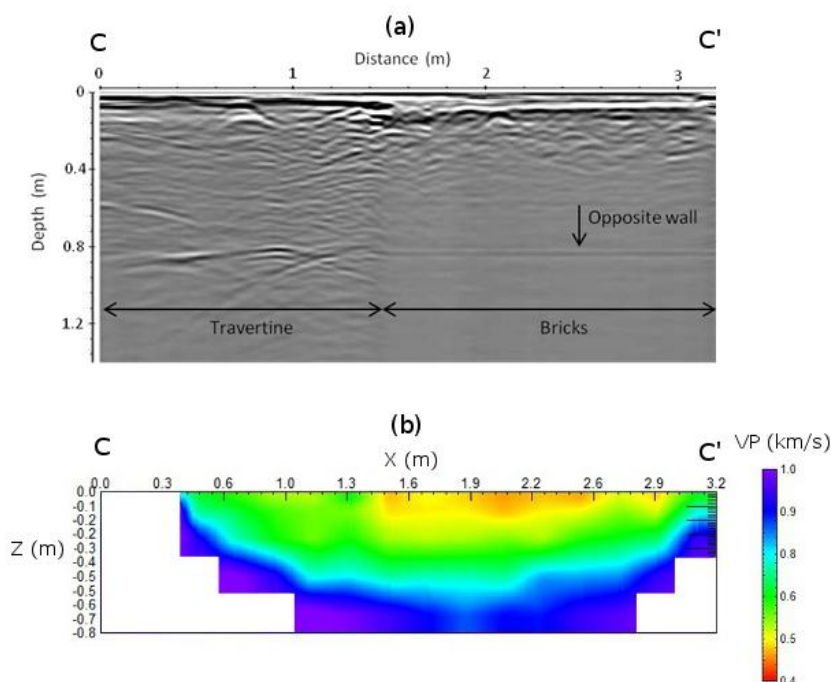


Figure 7 : C-C' GPR Profile (a) and inverted model of the seismic line S1 (b) (see Fig.3 for location of profile).

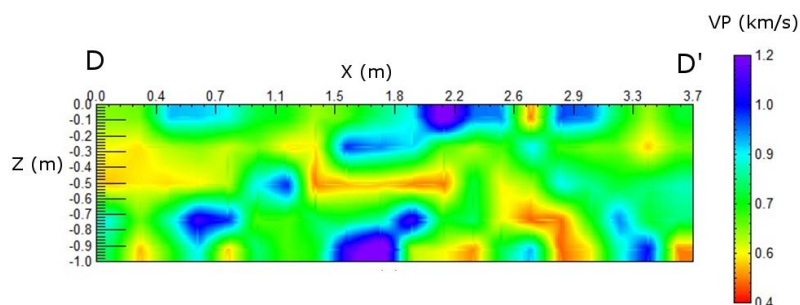


Figure 8 : Inverted model of the seismic line S2 (b) along the D-D' profile (see Fig.3 for location of profile).

CONCLUSION

The use of integrated geophysical methods, as GPR and seismic tomography, allowed us to characterize a pre-Trajan Roman structure, to assess the conservation status of the construction materials and to locate the major fractures and discontinuities, giving also quantitative indications about their geometry and typology. As a result we present in Fig. 9 the reconstructed model of the wall, where discontinuities and anomalies are highlighted. In particular, discontinuities were detected through the combined analysis of the GPR vertical and horizontal profiles and of the time-slices in both the travertine and the bricks. Where the time-slices are mapped without using a gain, the differences in terms of quality and composition of the construction materials become more evident, because the attenuation is directly correlated to the lithology.

In addition to this, the two seismic profiles confirm the evidences derived from GPR, stressing the difference between the two construction typologies (S1) or among the same typology (S2), in the case of an high degree of heterogeneity, highlighting the low-velocity zones, corresponding to poor mechanical properties.

The resulting high-resolution mapping of the wall reported in Fig. 9 confirms the consistency of the joint interpretation of different non-invasive techniques. These findings can help the archaeologists to plan accurately the future excavations, in order to preserve the integrity of the wall

and, consequently, of the precious surface mosaic. The joint interpretation procedure described above can be applied to vertical or horizontal structures (walls, concrete elements, foundations, etc.) with the aim to evaluate their reliability and providing safety indications for the restoration activities.

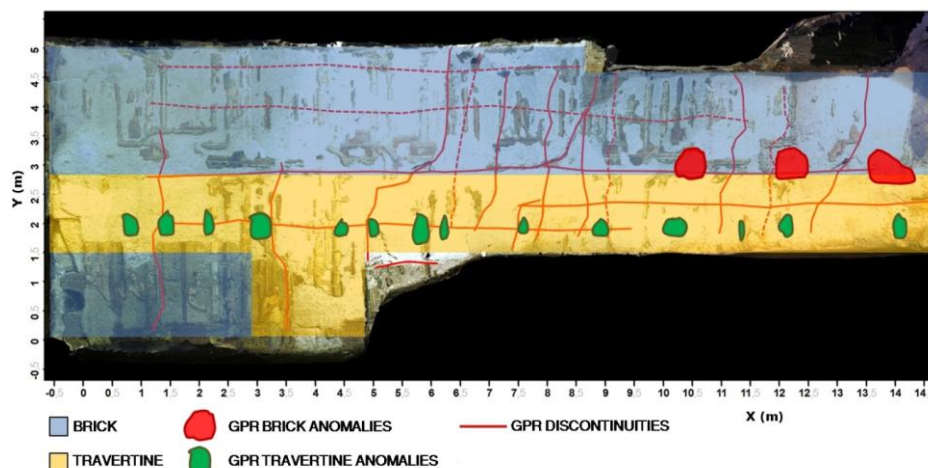


Figure 9 : Reconstructed model of the wall.

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