

# GPR Survey of Masonry Arch Bridges: A Study Case in Galicia (NW Spain)

Mercedes Solla, Henrique Lorenzo, Fernando I. Rial, Alexandre Novo, Belén Riveiro

University of Vigo – Escola Universitaria de Enxeñaría Técnica Forestal

A Xunqueira s/n – 36005 Pontevedra, Spain

[merchisolla@uvigo.es](mailto:merchisolla@uvigo.es), [hlorenzo@uvigo.es](mailto:hlorenzo@uvigo.es), [firm@uvigo.es](mailto:firm@uvigo.es), [alexново@uvigo.es](mailto:alexново@uvigo.es), [belenriveiro@uvigo.es](mailto:belenriveiro@uvigo.es)

**Abstract** – In the last years several cultural heritage organizations as ICOMOS or UNESCO have asserted the importance of using non-destructive methods to document historical monuments and sites, together with their current state of decay. According to these recommendations, the main goal of this study case is to analyze the potential of GPR as inner data source for the evaluation of ancient masonry arch bridges in order to determine the state of conservation and provide information about preservation and restoration. An ancient medieval bridge in Galicia (NW Spain) is surveyed using ground-coupled shielded and unshielded antennas with nominal frequencies of 200, 250 and 500 MHz, and with the aid of a total station for accurate positioning and topographic correction of the data collected. The interpretation of radargrams plus computer simulations - based on accurate graphic models obtained by close-range photogrammetry methods -, allow to extend both the historical-archaeological and the structural information of the bridge. After a simple processing flow, it has been possible to detect and map some structural elements of the bridge, as well as the presence of an unexpected reflector which could be an old hidden arch.

**Keywords** – GPR, masonry arch bridges, archaeology.

## I. INTRODUCTION

Despite GPR is one of the most recommended NDT methods in bridge inspection [3], the specialized bibliography does not show too many examples of GPR surveys on historical bridges evaluation, probably because non-destructive testing on ancient civil engineering structures with GPR is a relatively recent subject [8]. In this way, GPR studies applied to the evaluation of masonry arch bridges are still not very extended, being possible to find some selected examples, such as [2], [4]-[6], or [10].

After a deep historical review of ancient bridges in NW Spain, we selected the medieval bridge of San Antonio because it is one of the historical bridges included in the Galician cultural heritage catalogue [1]. It is a 13th century masonry bridge located in Cerdedo, southwest of Galicia (see Figure 1).

The bridge is 31 m long and has a slightly pointed profile (see Figure 2). The external structure consists of two semi-circular arches: a large one of 10.2 meters span and a smaller one of 4 meters span, both separated by a triangular buttress. At the time of the survey, the distance between the

arches and the river surface was 2 m for the small arch and 4.8 m for the large one. The river depth under the two arches was 0.2 and 1 m, respectively. There is a medieval flagstone path over the bridge which is about 3.5 meters wide (see Figure 3).



Figure 1. Location of the San Antonio medieval bridge (Spain).

The main goal of the study was to analyze the filling material homogeneity, identify different zones, detect hidden features (such as internal holes or cracks) and define the internal construction characteristics. Hence this information may be used to determine the state of conservation as well as to provide valuable information for preserving and restoring historical bridges. This information could also be useful for construction engineers to verify the structural stability of the bridge.



Figure 2. Medieval bridge of San Antonio (Cerdedo – Galicia).

## II. METHODOLOGY

The first GPR surveys were carried out with a bi-static 200 MHz unshielded antenna. This frequency was selected as low enough to reach the bridge foundations. The offset between transmitter and receiver antennas was set to 0.6 m (Figure 3). A total of three parallel lines, 45 m long each, were carried out with 1 m distance between transects. Common-offset point-to-point data was acquired with 10 cm in-line spacing, time window of 234 ns, and 512 samples per trace.



Figure 3. Acquisition tasks with the 200 MHz antenna.

In order to obtain more detailed information of the shallower filling material of the bridge, two surveys were acquired with 250 and 500 MHz shielded antennas together with an odometer wheel. Ground conditions made measurements difficult, as the bridge's floor consists on large irregular rocks which strongly interrupted the continuous movement of the survey wheel (see Figure 3).

Two longitudinal parallel profiles, 75 m long each, were gathered twice: First dataset with the 250 MHz shielded antenna, 5 cm in-line spacing, 200 ns time window, and 512 samples per trace. The second dataset with the 500 MHz shielded antenna, 2 cm in-line spacing, 90 ns time window, and 610 samples per trace.

The radargrams were corrected for topography by digital photogrammetry and total station data acquisition.

The accurate 3D model of the bridge obtained with the photogrammetric process was utilized to create synthetic models using GprMax software v2.0 [9]. These models have helped with field data interpretation. Ground Vision v1.4.5, ReflexW v4.2 and GPR-Slice v5.0 software were also used for data processing.

## III. RESULTS

Figure 4a shows an unprocessed radargram obtained with the 200 MHz unshielded antenna. Each radargram was fil-

tered applying the following processing sequence before interpretation:

- Time Zero / Dewow.
- Gain / Band Pass filtering.
- Topographic Correction.

Considering the structural dimensions of the bridge provided by the photogrammetric survey, it has been possible to make an estimation of the signal velocity in different zones of the bridge ranging from 8.5 to 11.6 cm/ns.

After processing (see Figure 4b), Figure 4c shows the interpretation of the processed radargram which presents some structural characteristics that can be easily identified as the arches and bridge foundations. A semi-flat reflection located between the two arches could be interpreted as an internal structural element for pier reinforcement – as they are documented in engineering books specialized in the topic [7] –, as a solid pier (unusual in medieval bridges) or even as it is filled with a compact material (the most probable hypothesis).

Observing the radargrams in Figure 4 it is possible to identify three big hyperbolic reflections, even though the bridge has only two visible arches (see Figure 2). This unexpected reflection situated between meters 0 and 6 in Figure 4, could be related to the presence of a hidden arch, however, there are not historical references of this third arch in the specialized bibliography [1]. Nevertheless, this interpretation could be ratified by the external geometry –the bridge is quite symmetric with respect to the large arch– and the presence of a dike in the left margin gaining land to the river-bed (see Figure 2). Under this unexpected reflection there is another reflection which could be associated with the old river-bed (see Figure 4c).

Considering this reflection as a hidden arch, the following step was to obtain some information about if it was empty or filled. Measuring the delay between the reflections from its key stone and the old river-bed (about 40 ns), and considering the air as the propagation medium, it would result in an 6 m high arch, that is, much higher than the right one. Further, if the arch was empty the polarity of the reflection in the arch-air interface should be the same than in the other two arches, which does not happen in this case (see Figure 4) –that is, the arch is not empty–, and the signal velocity in the filling material is lower than in the arch. The filling material seems quite homogeneous so it is not possible to appreciate significant internal reflections.

Finite difference time domain (FDTD) simulations of an arch with the same dimensions as the small arch and 2 m between keystone and river-bed, show the differences between an empty arch (see Figure 5a) and a filled arch (see Figure 5b) – considering a permittivity value of 8 for the

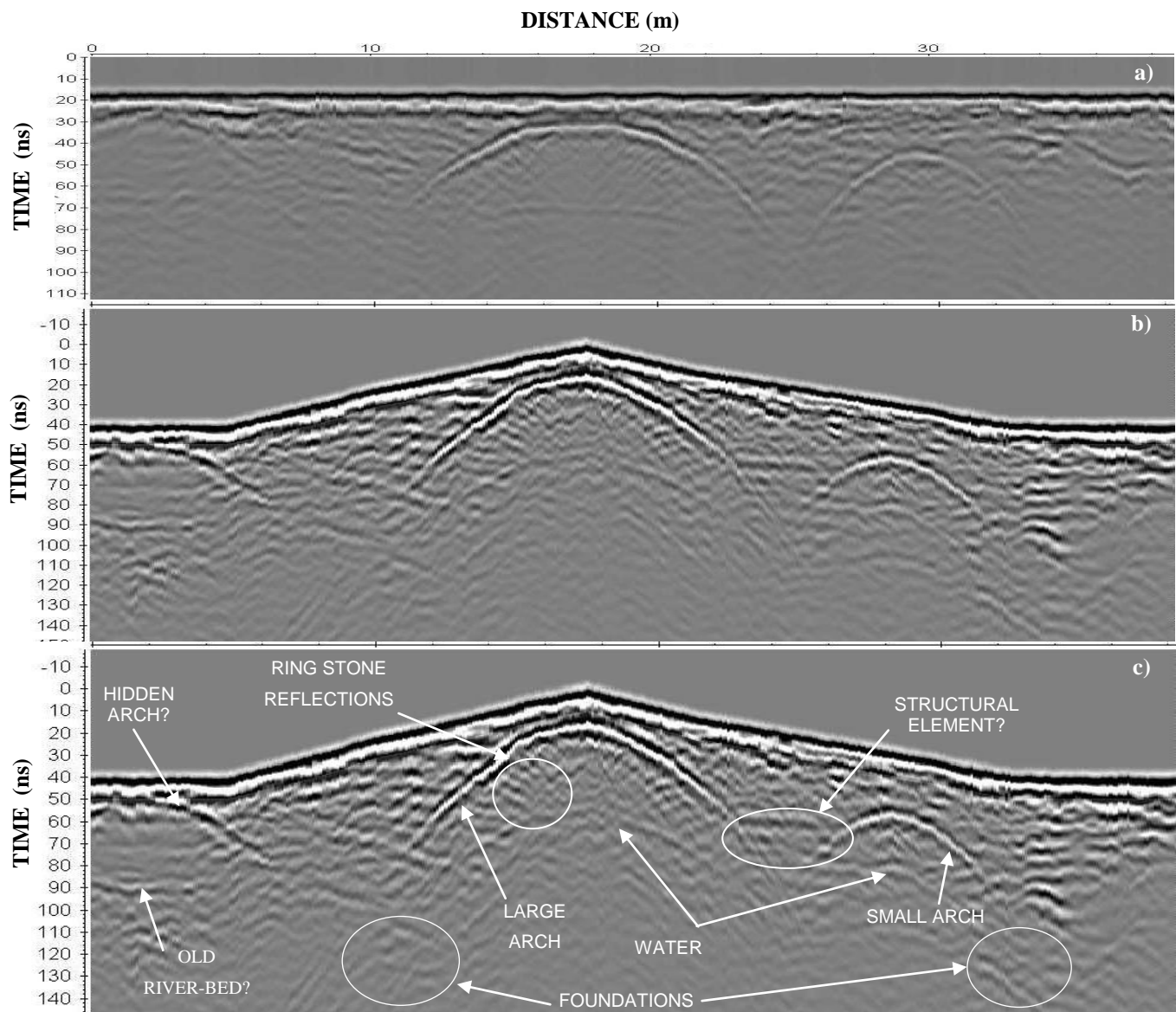
homogeneous filling material –. Comparison of both models show how the polarity of the arch - air interface (see Figure 5a) is different from the arch – filling interface (see Figure 5b).

The ring stone reflections produced in this kind of arches (see Figure 4), are explained by the FDTD model on the Figure 7. While ring stones are plain from the outside, the inside generally has a staircase shape.

From the precise photogrammetric data and the information provided by GPR, it was possible to build a synthetic model

of the whole bridge in order to facilitate the interpretation of the radargrams obtained (see Figure 6).

The simulation clearly shows reflections produced by the structural elements of the bridge, but also the presence of multiples from the arch, and the typical corner reflections produced in this kind of arches [11]. These complex reflection patterns difficult the detection of other reflectors affected by cluttering. In this way, it is hard to obtain in the radar data clear information about the foundations or filling material between the arches.



**Figure 4.** Radargram obtained with the 200 MHz unshielded antenna. a) Raw data. b) Processed data after a basic processing sequence. c) Interpretation of some of the main reflectors detected with this antenna.

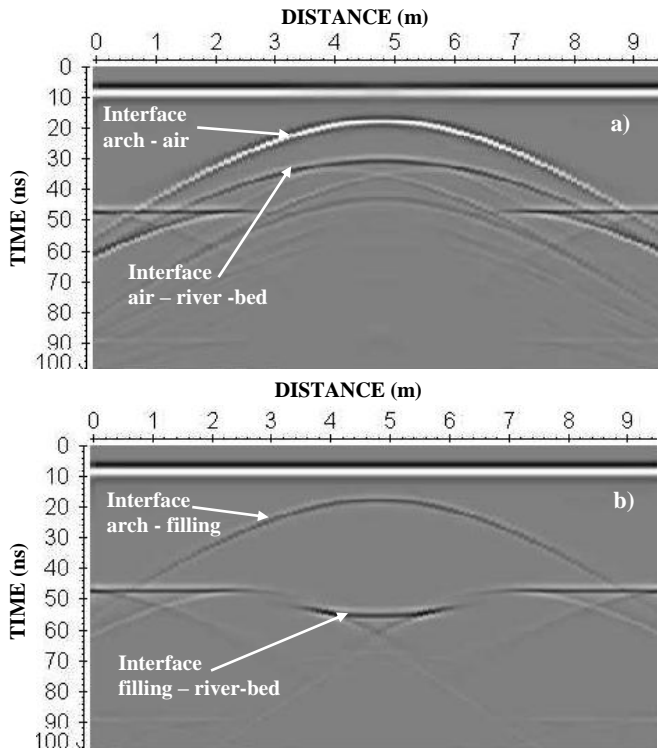


Figure 5. Simulated radargrams. a) empty arch. b) filled arch.

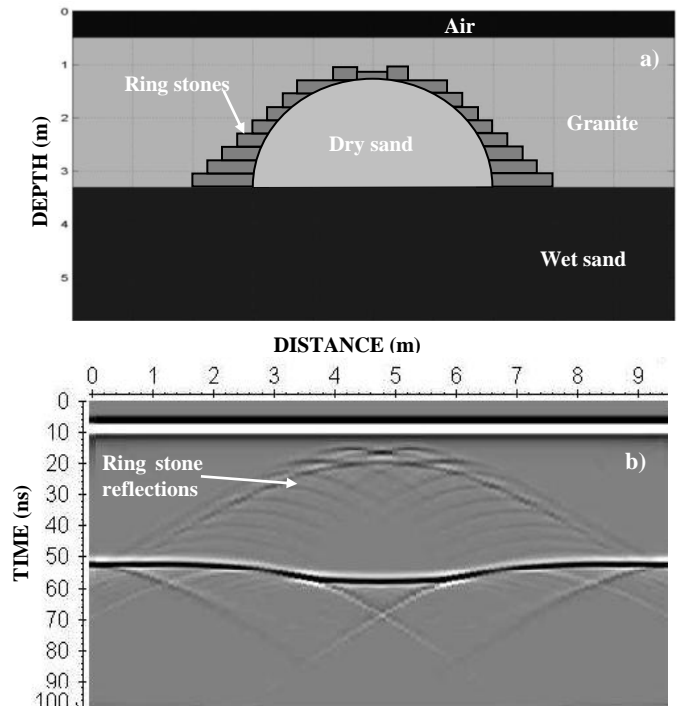


Figure 7. Synthetic model showing the effect produced by the ring stones of the arch. a) Base model. b) Obtained radargram.

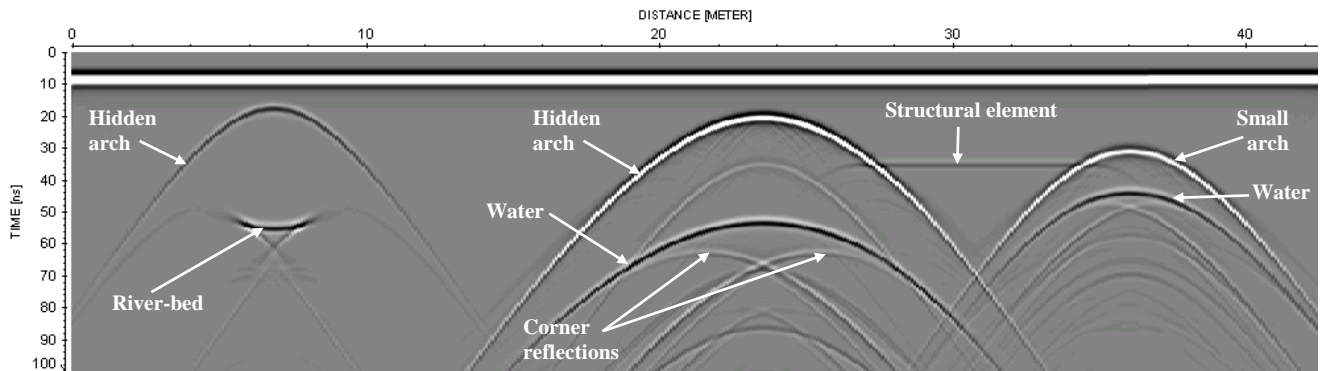


Figure 6. Synthetic radargram generated from the photogrammetric and GPR data.

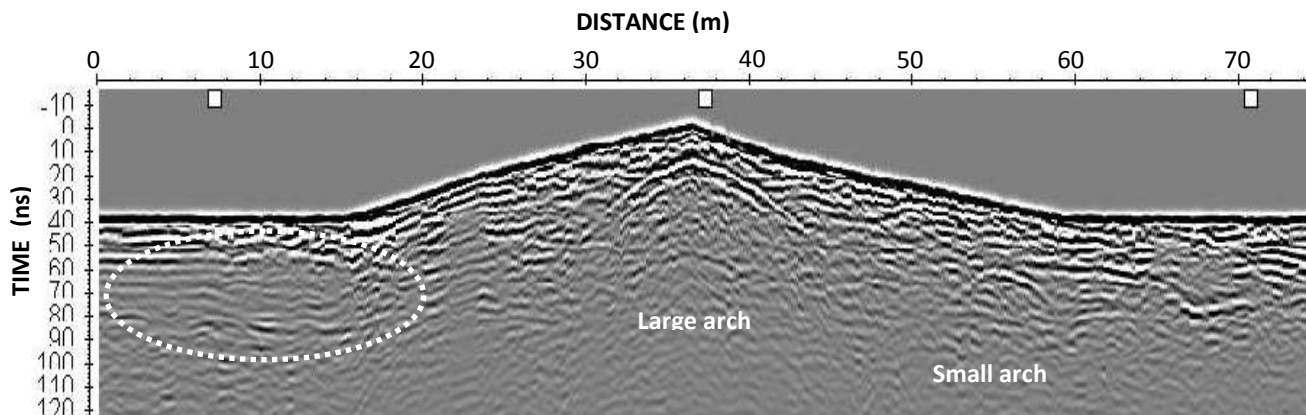


Figure 8. Longitudinal profile across the bridge obtained with the 250 MHz shielded antenna.

The profiles obtained with the 250 and 500 MHz antennas were started a few meters before the 200 MHz survey, with the goal of verifying the continuity of the reflected structure which previously was interpreted as a possible hidden arch. However, as it can be noticed in Figure 8, there is not a clear reflection from a hidden arch, and it seems like the reflected structure has certain continuity to the left. All this area seems to have a more homogeneous filling material. An explanation to this might be a bridge modification which caused a partial destruction of the arch and subsequent filling - including contiguous zones -.

#### V. FUTURE WORKS

An advanced interpretation of the GPR data, with special attention to the information provided by higher frequency antennas, will be used to define different areas in the bridge by their homogeneity in terms of signal response. This information, together with the data provided by close range digital photogrammetry will be utilized to model the structural behaviour of the bridge by finite elements (FEM) based simulations.

#### IV. CONCLUSIONS

The potential of GPR as an effective and versatile tool in the analysis of historical bridges was considered in this work. The results show how just a simple but careful data processing allowed extracting significant information concerning the bridge from both, a historical-archaeological and structural point of view.

FDTD modelling has shown its capabilities as an important tool for interpreting the complex pattern of reflections obtained in the radargrams.

The detection and accurate positioning of cracks, hollows or faults (some of them visible on the surface of the arches and pillars) was a difficult task, mainly due to the heterogeneity of the filling material, that result in many reflections and diffractions that usually cause a very hard interpretation.

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