Non-destructive GPR evaluation of underpass arch-shape structures

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Purpose In recent decades, road inspections have used automated vehicles that integrate LiDAR, GPR, and IRI measurements. GPR-data provide valuable information–typically about the pavement thickness–for road assessment. The aim of this work is to test the GPR-system to provide geometric information about underpasses of roads, principally related to the depth and span length. **Method** Both high and low frequency antennas (500 and 200 MHz) were used to determine the most appropriate survey methodology for our purpose. This technique was used to detect the different layers of an arch structure. To validate the method, GPR-data were compared with the ground-truth data provided by a mobile laser scanner. **Results & Discussion** The GPR results showed the potential of the system to obtain information about subsurface structures, and the arch geometry (depth and span length) were defined. However, the heterogeneity of the backfill over the arch made it difficult to use the field data we obtained. Finite-difference time-domain (FDTD) modeling was used in this work to understand the response of the radarwave and to assist in the data interpretation. The synthetic models were built from the orthoimage provided by laser scanner, defining the structure in fine detail, which resulted in large scale and more realistic models. Laser scanner errors in geometric measurements were lower than the 6 mm of the laser used as the ground truth for this work. By exhaustive interpretation of the field data–once they were analyzed through modeling–we found that the GPR-data are consistent with the laser scanner data and open the possibility of using GPR-information to obtain the geometry of subsurface structures for road inspections. This information could be useful to make structural calculations and predict critical failures.

INTRODUCTION

The highway Ourense – Celanova will become during the next years one of the main roads of inland Galicia (Spain) that will result in a quick connection route to the cities of Northern Portugal. This motorway is projected as a public – private partnership between the regional transport administration (Xunta de Galicia) and the construction companies Copasa SA and Extraco SA. This partnership includes private funding for the construction works and subsequent payment by indicators of management efficiency.

The infrastructure has a number of underpasses for the passage of wildlife animals, person and agricultural machinery. The underpasses consist of two reinforced concrete voussoirs placed on two small concrete walls (Fig.1). For each set of voussoirs there are three joining points, two between the walls and the voussoirs and one between the both voussoirs and the top of the structure. These underpasses suffer significant mechanical stress during construction and service life that must be monitored.

In the last decades, there has been a continuous increase in the use of non-destructive testing (NDT) to evaluate civil engineering structures[1].This work presents the use of non-destructive geodesic and geophysical techniques for the assessment of underpass arch-shape structures. Ground penetrating radar (GPR) was chosen since the method is a non-destructive geophysical technology that provides quantitative information about the subsurface structures, which cannot be inspected with the traditional optical technologies (i.e. total stations, LiDARs).GPR is one of the most frequently recommended NDT methods on civil engineering because it is a relatively quick technique that gives an overall qualitative internal image of the shallow subsurface. It provides high penetration depth and precise horizontal and vertical positioning. These two-dimensional images, called radargrams, are XZ graphic representations of the reflections detected. The X axis represents the antenna displacement along the survey line, and the Z axis represents the two-way travel time of the pulse emitted (in terms of nanoseconds). If the time required for the electromagnetic pulse to go from the transmitting antenna to the reflector into the ground and return to the receiving antenna is measured and the velocity of this pulse in the subsurface medium is known, then the position of the reflector can be determined. However, to date there have been few published studies on the dimensional and structural analysis of subsurface structures, probably because NDT on masonry civil engineering structures with GPR is a relatively new subject since the 1992s[2] as well as the geometric and interpretational difficulties of these complex environments, with some notable exceptions[3,4].

The analysis and interpretation of GPR data can be

complicated since many factors can adversely affect GPR waves, including ringing noise, diffraction events and reflection multiples. Numerical modelling has become an interpretational tool that can be used to compare processed GPR data to models to understand the radar-wave propagation phenomena and to facilitate GPR data interpretation[5]. When more sophisticated interpretations are required, the finite-difference time-domain (FDTD) technique has evolved into one of the most popular advanced modelling tools for simulating the propagation of the GPR waves in different media[6]. This modelling method allows for the extraction of subtle information from the real data, such as diffraction patterns and the presence of reflection multiples[7].

To analyze the viability and effectiveness of GPR this work includes the use of LiDAR methods. Three-dimensional laser scanning is the most evolved technology in the metric documentation of built up structures mainly due to the high rate of measurement over the structure surface with millimeter accuracy[8] and incorporation of texture information of the objects to the metric laser data. The metric information obtained by LiDAR allows calculating the most appropriate average velocity of the radar-wave for different media[9]. Moreover, the precise geometric data provided has shown its capabilities as inputs to create large scale and more realistic FDTD numerical models[10].

Fig.1. Underpass arch-shape structure, under survey in the highway Ourense-Celanova before filling and structural settlement.

METHODOLOGY

This work aims with the dimensional analysis of underpass arch-shape structures by means of NDT techniques. A GPR data was carried out to obtain inner information of the structure and, for target identification, the approach included the use of mobile LiDAR, which provides more detailed information about structural geometry and shapes. Moreover, to improve interpretations of the field GPR data, FDTD simulations were built from the accurate geometry provided by LiDAR.

Ground penetrating radar

The GPR survey was conducted using a RAMAC GPR system from MALÅ Geoscience. For the pur-

pose of this work, both high and low frequencies were chosen(500 and 200 MHz, respectively). These frequencies were selected as the most optimum due to its compromise between penetration and resolution. The 500 MHz frequency provides on the order of 6 m in depth penetration (under optimum conditions) and a spatial resolution of 5.75 cm. Nevertheless, although the 200 MHz frequency provides a spatial resolution on the order of 14.25 cm, the depth penetration results in about 12 m. The value for spatial resolution was calculated considering an average radar-wave velocity of 11.5 cm/ns, as reported in the literature for dry limestone soils[11].

GPR profiles transverse to the arch structure (in the direction of traffic flow), were gathered twice: First dataset was conducted with a biestatic200 MHz unshielded antenna. This frequency was selected as low enough to reach the entire structure. The offset between transmitter and receiver antennas was set to 0.6 m (Fig. 2). The profiles were carried out using the common-offset-mode through the surface of the highway over the underpass. The survey parameters assumed were10 cm trace-intervals, total time window of 200 ns, and 449 samples per trace.

Fig.2. Data acquisition setup composed of the 200 MHz unshielded antenna.

The second dataset was conducted with the biestatic 500 MHz shielded antenna to obtain more detailed information of the shallower backfill material over the structure.The survey parameters selected were 5 cm trace-intervals with a 75 ns total time window and 519 samples per trace. In this case, to measure the profile length, the GPR antenna was mounted on a survey cart with encoder (odometer wheel).

The GPR data collected was processed with ReflexW v.5.6 software to correct the down-shifting of the radar section due to the air-ground interface and to amplify the received signal, as well as to remove both low and high-frequency noise in the vertical and horizontal directions. The processing sequence applied was: time-zero correction, dewow filtering, gain application, spatial filtering ("*Subtracting average*"), and band-pass ("*Butterworth*") filter.

LiDAR

Geometric data were acquired using a mobile LiDAR from Optech Lynx (Fig. 3). The system integrates a navigation GPS/INS system from Applanix (POS 520 - 2 GPS antenna), 2 LiDAR scanners from Optech and 4 digital cameras from Jai (BB 500GE). The metric characteristics of the Lynx system are shown below:

- Maximun range: 200 m
- Range precision: 8 mm (1 σ)
- Absolute accuracy: 5 cm (1 σ)
- Scan frecuency: 80 – 200 Hz
- Scanner field of view: 360º
- Laser measurement rate: 75 – 500 kHz

Fig.3. Mobile LiDAROptech Lynx.

Mobile LiDAR survey began and finished with the acquisition of 5 min of GPS data in an area with small PDOP (high GPS precision). The complete time of the survey was 14 min. Scanner and photographic data are only taken while the van is moving to avoid the excess of data. The synchronization of the data from the different sensors of the mobile unit is achieved using the time stamp and the PPS of the GPS/INS system. A total of 240 million of geometric points were acquired during the survey.

The data processing is performed using Applanix POSPac and Dashmap software. The first one corrects the GPS information using a RINEX file from a base station. In addition, combines, using a Kalman filter, the data from the GPS with those obtained from the inertial navigation system (INS) and distance measurement indicator (DMI). The corrected trajectory file exhibits a precision higher than 2 cm in X Y and higher than 4 cm in Z.

Dashmap combines the range and angle information obtained from the Optech scanners with the trajectory information from PosPAC.

The point cloud obtained will be managed using the QT Modeler software in addition to Matlab and AutoCADsoftwares to obtain the images (transversal sections) to be used for numerical simulation.

FDTD modelling

The overall objective by using numerical simulation is to assist in the interpretation of the processed field data acquired by GPR. The synthetic results can supply important additional information for the advanced interpretation of GPR data by rendering the complex pattern of reflections obtained. This allows identifying clutter reflections from the field data and extracting subtle interpretational information suchas the timing, presence of reflection multiples, and target material properties.

To construct the synthetic models, the GprMax v.2.0 software[12]was used, which is an electromagnetic wave simulator for GPR using the FDTD method. Simulating the GPR response from a particular target using a FDTD method, Maxwell's equations require to be solved with the appropriate initial and boundary conditions and the adequate description of the material properties. The precise geometry provided by LiDAR methods was used to elaborate on the FDTD modelling using the Matlab software. Knowing the real geometry of the underpass arch-shape structure can provide useful information towards the creation of more realistic synthetic models. The need to discretize the volume of the problem space and the staircase approximation of curved interfaces to the real boundary result in an excessive computer memory requirements as well as large execution time. To reduce the computational time, the synthetic models were elaborated using a mixed model of parallelization in GprMax based on a hybrid message passing interface (MPI) and open multi-processing (OpenMP) parallel programming in GprMax software.

The synthetic models were created with a small spatial-step equal to 35 mm, and the excitation pulse was a Gaussian of 200 MHz centre frequency. The trace step and the total time window were 0.1 m and 160 ns, respectively, and were defined by 230 traces per sample. This approach encompasses the geometry of the arch in fine detail. The electromagnetic properties assumed for media characterization are shown in Table 1. These values were obtained from the published literature[13]. Two different media were considered simulating the reality. Once the arch was placed, it was recovered by a compact layer until 1.5 m over the keystone (backfill 1), and a second layer (backfill 2) was used to fill until the road level (2 m more).

Material	Conductivity (Sm^{-1})	Relative permittivity
Air	0	1
Backfill 1	0.001	6
Backfill 2	0.0001	7
Concrete	1	10

Table 1. Electromagnetic properties for media characterization.

RESULTS AND DISCUSSION

Figure 4 shows the GPR data acquired with the 200 MHz unshielded antenna over the underpass in the transversal direction of the structure. Observing the radargram, it was possible to identify the reflection produced at the arch-air interface (red arrow), as well as the one due to different layers of materials used to fill the arch until the road level (white arrow). The orange arrow (4.5 m approximately) indicates the placement of a backfill until the haunch of the arch (between the springing and the keystone) to ensure the stability of the underpass structure (Fig. 1).

Fig.4. GPR data acquired with the 200 MHz unshielded antenna.

To determine the depth of the reflections identified, the velocity of propagation was set to 11.5 cm/ns, as reported in the literature for dry limestone media[11]. For calculations, the difference pick application[9] was used considering the wave travel-time difference from reflections at known distance (for example the air interface at the top and the one for the first layer). In this way, the depth of the arch's keystone (from the road level) resulted on the order of 3.75 m (65.8 ns), and the depth of the reflection generated at the interface between different layers was 2.18 m (38 ns), which is comparable to the reality. Moreover, the arch's span was estimated in approximately 12.0 m (whose real dimension is 12.8 m). In this case, using the velocity of propagation for concrete media (5.5 cm/ns)[13], the radius of the span was determined by adapting a diffraction hyperbola[9] to the hyperbolic reflection generated at the arch-air interface.

On the other hand, the 500 MHz data collected have not revealed interesting details of the shallower sub-surface over the underpass structure. Although the spatial resolution is greater than 200 MHz frequency,and differences in layerwere identified (the white arrows in Fig. 5), the depth of penetration was not enoughto reach the structure with the selection of a total time window of 75 ns. Under optimum conditions, this time window allows to reach until 4.0 m in depth considering a velocity of propagation 11.5 cm/ns. The first interface between different layers at about 2 m was even not detected. Reflections were recorded only until 1.75 m (30 ns)instead of the expected 4.0 m (75 ns), which could be most probably caused by a severe attenuation of the electromagnetic signal.
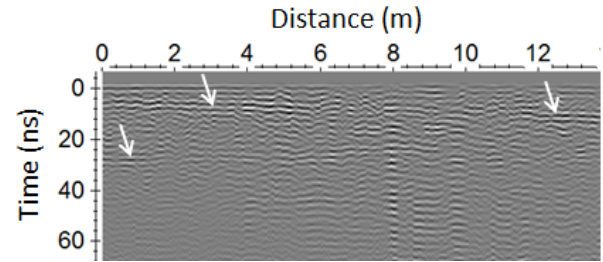

Fig.5. GPR data acquired with the 500 MHz shielded antenna. The white arrows indicate differences in layer.

The resultobtained from the mobile LiDAR is a geo-referenced point cloud (WGS84 datum). This point cloud was managed using QT Modeler software (Fig. 6).
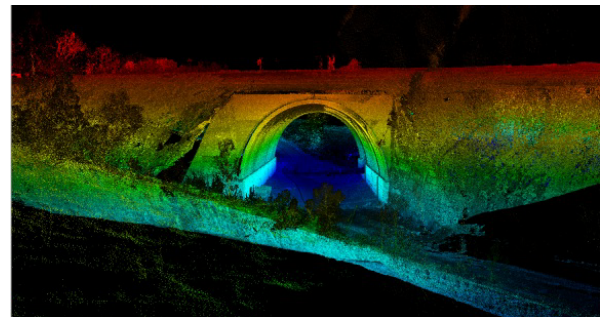

Fig.6. Point cloud of the structure after filling.

Finally, a transversal section of the point cloud is extracted from the point cloud (Fig. 7) to be used in combination with the GPR data. QT Modeler, Matlab and AutoCAD software is used in this step.
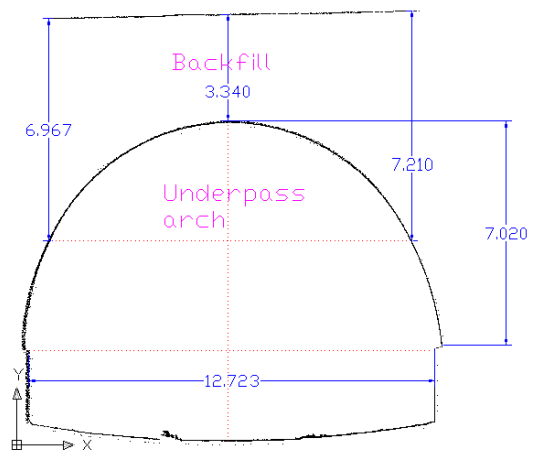

Fig.7. CAD profile of the arch and backfill. Lengths are provided in meters.

FDTD modelling was used to analyze and to understand the pattern of reflections obtained from the field GPR data. The synthetic model used for simulations was built from the CAD profile in Figure 7. Once the synthetic results were provided, they were exported to ReflexW software and filtered using a very similar processing sequence than that used for the field data.

Figure 8 shows the synthetic results generated, where relevant interpretational reflections were identified such as the hyperbolic reflection from the arch-air interface (R1), and the reflection caused by the dielectric contrast between the backfill layers used to fill the arch (R2), in addition to reflection multiples (R3).
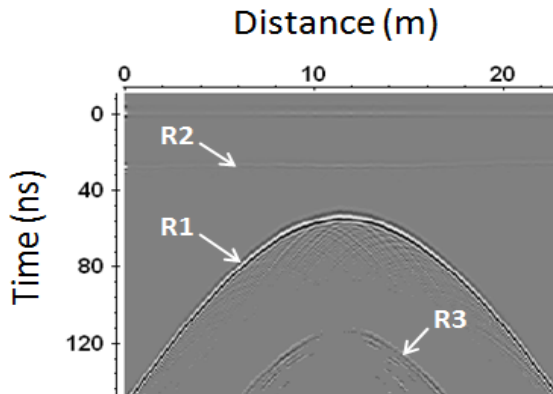

Fig.8. Synthetic results showing relevant reflections to assist in the interpretation of the field data: the reflection produced by the arch-air interface (R1), the reflection generated at the interface between different backfill layers (R2), and reflection multiples (R3).

CONCLUSIONS

The viability and effectiveness of the GPR was demonstrated when surveying subsurface structures in road inspections. Nevertheless, FDTD modelling was used to understand the pattern of reflections obtained and to assist in the interpretation of the field data. The synthetic models were built based on the accurate geometry provided by mobile LiDAR technology. This approach encompassed the underpass arch-shape structure in fine detail, and more realistic and large scale models were built. using a mixed model of parallelization. Using a mixed model of parallelization, the simulation allowed the extraction of subtle interpretational information such as reflection multiples, in reasonable time.

The use of GPR can provide a solution for engineers engaged in creating or improving the processes and services related to the evaluation, rehabilitation and maintenance of on-road civil structures.

Acknowledgements

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