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Three-dimensional ground-penetrating radar methodologies for the characterization and volumetric reconstruction of underground tunneling

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HIGHLIGHTS

- Documentation and characterization of underground tunneling space by GPR.
- Volumetric reconstruction that allows determining numerical approximation of volumes.
- Geometrical dimensioning of the structure from the volumetric reconstruction.
- Detection of moist areas from the attenuation of the GPR signal.
- FDTD modeling to assist in the interpretation of the field GPR data.

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ABSTRACT

This work presents the documentation and characterization of an ancient underground concrete tunnel using the ground-penetrating radar (GPR) method. Three-dimensional imaging methodologies were applied to create an accurate volumetric reconstruction of the underground tunneling space and the whole framework of galleries composing the main structure, which enabled for the dimensioning of the structure. Problems of moisture were also detected in a particular sector of the tunnel. In addition, FDTD modeling was used to improve the understanding of the GPR signal propagation and to assist the interpretation of the field GPR data. Both field and synthetic data have shown the capabilities of the method for the evaluation and characterization of this ancient construction.

1. Introduction

Tunneling detection becomes relevant based on a civil engineering point of view, due to the momentous importance of knowing the underground space distribution. In addition to the interest with regard to their influence in the settlement and disposition of the subsoil structure [1,2], the documentation of these constructions also holds connotations of historical and cultural character, architectural interest, tourist attraction or military and defense implications [3–5]. Therefore, their exact location and geometry provides additional information to plan and perform maintenance and repair tasks, which enable for the preservation of their structures and content in optimal conditions [6,7].

This work presents the evaluation and characterization of an existing tunnel located within the premises of the Spanish Naval Academy of Marín, Galicia, in the northwest of Spain (Fig. 1). The galleries of the tunnel develop different functions, namely: ventilation, general storage and military training site for the students belonging to the Spanish Navy Marines Corps, which is the oldest existing Naval Infantry Force in the world [8].

The ground-penetrating radar (GPR) is a geophysical commonly used technique, with a wide range of applications. There have been published numerous studies on different fields, such as military

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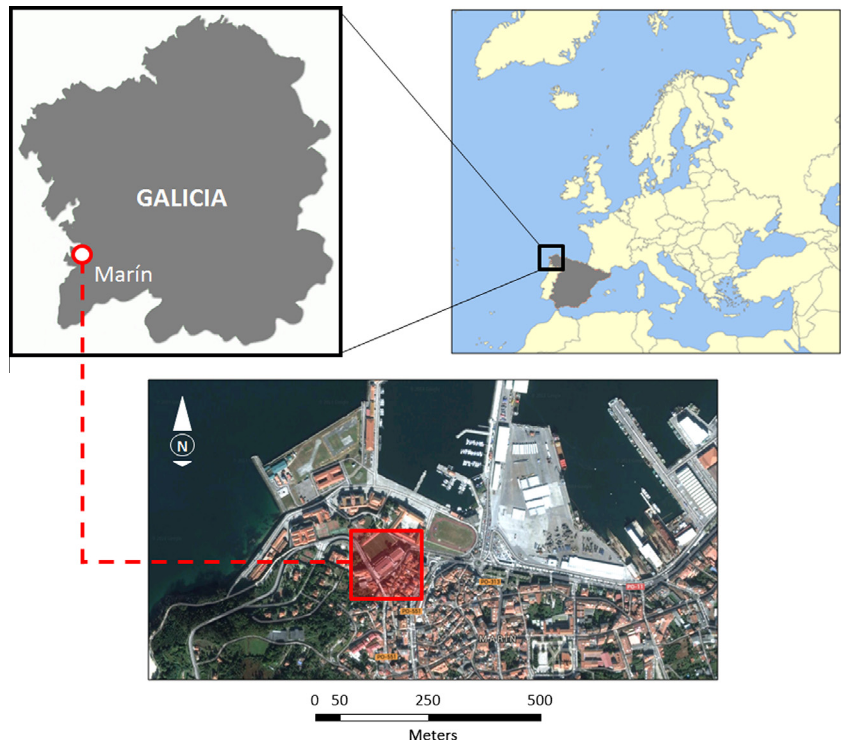

Fig. 1. Location of the prospected area in Europe and specifically in Marín (Galicia, northwest of Spain).

(mine detection [9,10], human remains and life detection [11]), civil engineering (pavement control and integrity of landing runways [12], pathologies in construction [13,14], location of buried structures [15]) and also in geology (detection of subsoil pollution [16] and freshwater bathymetries [17]).

Therefore, GPR is proposed in this paper as a solution for the documentation of an underground tunnel because of its rapidity and suitability as non-destructive technique. So that, it is the ideal solution in comparison to other more invasive methods, such as excavation or underground tasting, that may deteriorate the structure of the tunnel and/or its content [18,19].

The GPR method has proven its suitability for providing high image quality results and is a well-recognized prospecting technique by the scientific community [20]. Nevertheless, there still remains some skepticism among the non-geophysical audience, promoted by the difficulty for the understanding of the GPR images. The interpretation of the radargrams (2D GPR images) is not trivial and the use of 3D processing and visualization techniques, has achieved the agreement by the non-expert community in safety underground investigations [21]. Using 3D processing and visualization produces more realistic images of the underground spaces, which allows not only for the location, but also for the 3D reconstruction of underground and buried constructions [22,23]. Therefore, an advanced 3D visualization methodology is presented in this work to provide better interpretation of the results and the volumetric reconstruction and dimensioning of the tunnel. These 3D images provide an accurate and intuitive display of the underground distribution, easily understood even by non-experts in the subject.

Numerical simulation was additionally used in this work to assist in the interpretation of the field GPR data. Specifically, Finite-Difference Time-Domain (FDTD) modeling was considered, since the method has demonstrated its capabilities to improve the understanding of the electromagnetic waves propagation through the media [24].

2. Materials and methods

2.1. Tunnel description

It consists of an underground tunnel with symmetrical geometry composed by a central corridor and lateral branches (Fig. 2A) that presents a final trifurcation of galleries (Fig. 2B). The main corridor presents two different levels of the tunnel, which are separated by a pronounced ascendant ramp at approximately the middle of its length (Fig. 2C). Some lateral branches present also an initial sector with ascendant slope, as illustrated in Fig. 2D. The underground construction is a concrete solid composed by several blocks seated one above the other, whose top ends in a concrete slab resulting in a sports court.

Moisture and condensation problems were observed in certain areas of the ancient concrete construction (Fig. 2E), possibly caused by the poor maintenance of some water pipes existing through one of the lateral sections of the subsoil of the structure. These water pipes are supposed to lead water with chloride content from the swimming pool, near to the tunnel, to the maintenance room and vice versa. Regarding these moisture evidences, it must be also taken into account the close presence of the sea, upon which the newest military installations were built. Moreover, the geographical location of the study site could have also affected the integrity of this ancient construction. That is supported by the location of the village of Marín (Fig. 1) in the Autonomous Community of Galicia, which is characterized by adverse weather conditions with high levels of humidity.

2.2. Field data acquisition

Three-dimensional (3D) GPR methodologies were performed in this work (Fig. 3A). Equidistant parallel 2D-lines in only *x*-direction were acquired on a regular rectangular grid (40×20 m size) with a space between profile lines of 20 cm. The GPR data were collected using a RAMAC/GPR system from MALÅ Geoscience and a central frequency of 500 MHz (Fig. 3B). The GPR survey was carried out using the common-offset mode with the antenna polarization perpendicular to the direction of data collection [25]. Data was acquired with 2 cm trace-interval or in-line spacing of traces, with reflections collected within a total time window of 75 ns and defined by 512 samples per trace. For trace-interval distance calculation, the GPR antenna was mounted on a survey cart with encoder (odometer wheel).

2.3. 3D data processing

GPR-Slice software [26] was used for the three-dimensional (3D) data processing. The first step, previous to the elaboration of the 3D cube, was to filter the raw