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Reflection waveforms occurring in bistatic radar testing of columns and tree trunks

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HIGHLIGHTS

- Bistatic radar system analysis.
- Analysis of radar wave propagation in cylinders.
- Numerical, laboratory and real radar data.
- Tree trunk and concrete column analysis.

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ABSTRACT

Ground-penetrating radar is a non-destructive inspection device which is not often applied to cylindrical media. In this paper, we extend our previous analyses of monostatic GPR waveforms to two bistatic radar configurations for cylindrical objects: 1) Single-offset radar system, where two antennas are simultaneously rotating around the cylinder, 2) multi-offset radar system, where only a receiving antenna is rotating around it. Analyses were performed through numerical experiments with gprMax2D, straight-ray analytical solutions, laboratory and real case studies. The complex real case studies highlighted the benefit of combining bistatic and monostatic radar data acquisitions to better resolve unknown internal structures.

1. Introduction

Ground-penetrating radar (GPR) is a powerful non-invasive tool for under-surface structures detection. Its functioning is based on scattering of electromagnetic waves that are emitted from a transmitting antenna and collected by a receiving antenna [1–3]. GPR has been used in many fields, such as civil and transport engineering [4–6], environmental applications [7–10], archaeology [11–13], and geophysics [14–16]. Most of these applications involve planar model configurations. For those cases, the interpretation of GPR images is well described and relatively intuitive. Nevertheless, data collection for other shapes, such as cylinders (columns, tree trunks, etc.), is more complex to interpret [17]. The context of our research is related to tree trunk inspection with GPR in order to predict tree trunk collapses caused by voided wood. For this application, a circumferential data acquisition is needed. Therefore, this paper is dedicated to the analysis of electromagnetic wave propagations in cylinders and resulting GPR images.

In a planar GPR image, one can observe hyperbolic reflection curves originating from buried objects (rebars, pipes, landmines, etc.) [18–21] or continuous reflection curves indicating different layers (road layers, groundwater table, etc.) [22–24]. However, in cylinders the electromagnetic waves propagate differently due to their curvature and, therefore, many cases of multiple reflections from the cylinder-air interface occur. In our previous research [25], we described reflection curves occurring in cylinders using a monostatic radar system (a single antenna for transmitting and receiving). Yet, in a bistatic radar system (one transmitting and one receiving antenna), it is possible to observe a series of interesting wave propagation paths. A bistatic acquisition also provides additional information about the inspected medium thanks to a different accessibility of the antennas to the medium. The reflection curves do highlight not only the position of an under-surface object, they can also be used to determine the electromagnetic properties of the medium. Therefore, it is worth to recognize as many reflection curves as possible in order to collect more

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information about the investigated medium. Reflection curves occurring in cylindrical structures were observed by Nuzzo and Quarta [26] and Bonomo et al. [27] who studied protection of cultural heritage. Persico and Soldovieri [28] and Leucci et al. [29,30] studied the influence of the use of the monostatic and multistatic configurations on column reconstruction tomography. GPR inspection of tree trunks was performed by, e.g., Nicolotti et al. [31], Lorenzo et al. [32] and al Hagrey [33].

The objective of this paper is to analyse reflection curves appearing in radar images of cylindrical structures obtained with the use of the GPR in bistatic mode (transmission). To make the link with our previous research, we compare our new results with the data collected with the use of a monostatic radar system. Specifically, both single-offset mode, where the antennas are opposite to each other and rotate around the object with fixed spacing, and multi-offset mode, where the transmitter stays at one position and the receiver rotates around the object, were considered. Firstly, we performed numerical simulations using the gprMax2D software [34,35], which solves the two-dimensional Maxwell equations using the Finite-Difference Time-Domain (FDTD) method [36] and which is specifically dedicated to GPR applications. Then, several possible propagation paths were observed and analysed with the help of snapshots of the electromagnetic field propagation made with gprMax2D. Using the straight-ray approximation, we analytically derived the shapes of the reflection curves of a circular inhomogeneity in the cylinder for easier determination of its position, shape and size, and we compared them with the reflections occurring in the numerical simulations and real radar images. We also performed laboratory measurements of a tree trunk model in the lab. Finally, we performed radar measurements for two real case studies to compare the real data with the simulated ones and those obtained in the laboratory. Specifically, we inspected a reinforced concrete column and a tree trunk with a cavity. For these measurements, we used a frequency-domain monostatic radar system and both bistatic radar configurations described above.

2. Numerical simulations

To better understand data obtained by a circumferential data acquisition scheme, we performed numerical simulations of radar measurements around a simple cylindrical model. Fig. 1 shows the two considered radar configurations: (a) with the transmitter and the receiver opposite to each other and rotating around the medium, (b) with the transmitter at a fixed position and the receiver rotating around the medium. Similarly to our previous research [25], our model was composed of two cylinders filled with sand and air, respectively.

To examine possible GPR images for this radar configuration, we used the gprMax2D (open source) software [34,35] which simulates propagation of electromagnetic waves and is specially dedicated to GPR applications. For the simulations, the relative permittivity of the sand was set to $\varepsilon_r = 3$ and electric conductivity was set to $\sigma = 0$S/m. The operating source was a Ricker wavelet with a centre frequency $f_c = 900$ MHz. The spatial resolution of the numerical model geometry in the x and y directions was set to 2,5 mm. For all our GPR images, we applied an exponential gain function.

In order to understand the simulated GPR images, the propagation paths were analysed and possible reflection waveforms were derived. To inspect possible propagation paths in the cylinder, we observed the time-lapse electromagnetic field distribution simulated by gprMax2D.

In our previous research, we observed two major ways of propagation as displayed in Fig. 2: 1) straight-ray, and 2) total internal reflection (TIR). The straight-ray approximation is a one-dimensional propagation of the signal which is a relatively good approximation for not very complex media. We used this term also for the direct multiple reflections and composed linear reflections described below. The TIR is a phenomenon occurring when a wave is scattered from electromagnetically denser medium to a less dense medium with an angle of incidence larger than the so-called critical angle. When these two conditions are fulfilled, the wave is fully reflected back to the medium with an angle which is identical in the opposite direction to the angle of incidence. In this case, the signal is reflected along the inner edge of the medium and its path has the shape of a regular polygon (from a pentagon up to a circle). In this paper, we represent the TIR as a circle or a part of a circle to show the path more easily in our images. Nevertheless, in the calculations, it was represented as a 5-sided regular polygon. This path was the most relevant for our setup as it was the shortest path avoiding internal voids. To express the reflection curves in the radargrams, simplified formulas in Eqs. (1) and (2) were used to obtain the propagation time of the signal:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (1)$$

where v is the wave propagation velocity [m/s], c is the speed of light in vacuum [m/s], and ε_r is the relative permittivity of the medium [dimensionless].

$$t = \frac{d}{v} \Rightarrow t = \frac{\sqrt{\varepsilon_r} \cdot d}{c} \quad (2)$$

where t is the propagation time [s] and d is the length of the propagation path [m].

Fig. 3 shows reflection curves simulated for a monostatic radar system, where interfaces 1 and 2 are the closest and the furthest points on the void edge, respectively, interface 3 is the opposite side of the medium, and TIR is the total internal reflection in the model (see Fig. 2a). The TIR continues its propagation along the internal edge of the medium and if the inner edge acted as a perfect

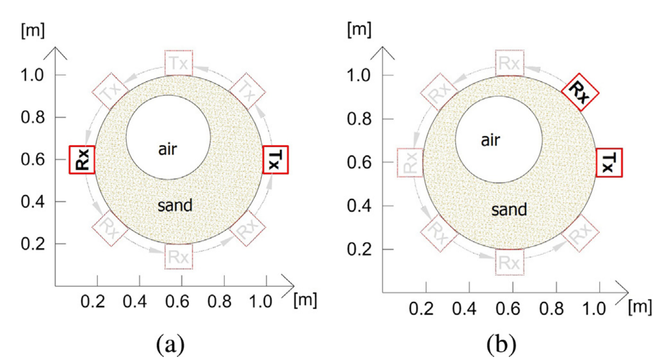

Fig. 1. Model geometry used for the numerical experiments with the single-offset (a) and multi-offset (b) radar antenna configurations.

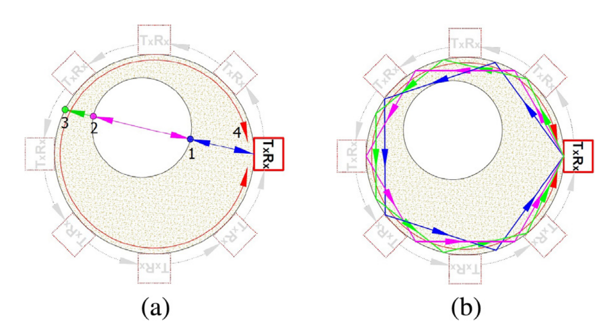

Fig. 2. Main wave propagation paths obtained by monostatic GPR: (a) 4 paths of straight-ray propagation, (b) detailed total internal reflection (TIR).