GPR resolution in NDT studies of structural elements : experimental methodology and examples

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Abstract

Ground penetrating radar (GPR) is a non-invasive geophysical technique that provides high resolution images of the inner media. It has been widely used in civil engineering and superficial geology in order to map shallow structures. The aim of these evaluations uses to be to obtain an imaging the subsurface with maximum resolution. Horizontal and vertical resolution are related to the ability of the system to detect as different anomalies two close targets placed in the same plan or in a vertical plan, respectively. In GPR studies, both properties depend on the antenna characteristics, on the emitted wave, on the radar acquisition parameters and on the medium properties. To be familiar with the resolution of the different GPR antennas in diverse media is basic information to prepare GPR surveys and to interpret raw radar data. In this work, we present a resume of several simple experiments made with two commercial 1.0 and 1.6 GHz centre frequency antennas. A set of examples showing radar raw and processed data in different cases (concrete, reinforced concrete and masonry) is also shown. Raw data were obtained during the evaluation of modern or ancient structures. The images obtained in these evaluations are compared to the results obtained in the laboratory measurements. All these GPR images are examples referred to the ability of the radar survey to evaluate different kind of structures and elements.

Résumé

Le radar (en anglais GPR pour Ground Penetrating Radar), est un outil qui rend service à une technique de prospection géophysique non-invasive. On retrouve le GPR lors de nombreuses études en génie civil et en prospections géologiques superficielles. L'objectif des différents travaux est généralement d'obtenir des images d'une notable résolution de l'intérieur des milieux ou des éléments prospectés. Les notions de résolution horizontale et verticale font référence à la capacité de l'antenne à distinguer deux objets enfouis et placés soit sur un plan horizontal soit sur un plan vertical. La différence est visualisée comme deux anomalies différentes dans le radargramme. Ces deux propriétés (résolution horizontale et verticale) vont dépendre des caractéristiques de l'antenne, des ondes électromagnétiques émises, des paramètres d'acquisition et des propriétés des matériaux sondés. Connaître la résolution prévue à chaque différent sondage constitue une information importante afin de préparer l'acquisition des données et pour une convenable interprétation finale. Le travail de recherche que nous présentons expose les résultats de différents essais de laboratoires traités afin de permettre d'approcher à la capacité de résolution d'une antenne commerciale de fréquence centrale 1.6 GHz. Les résultats sont comparés avec les images obtenues au suivi de sondage sur des ouvrages de génie civil, de bâtiment en béton ou maçonneries et de monuments historiques.

Keywords

Ground penetrating radar, NDT, concrete, masonry.

1 Introduction

Ground-penetrating radar (GPR) evaluations are widely used in non-destructive studies of civil engineering structures. This geophysical technique provides images of the inner structures in the evaluation of masonry arch bridges ([1]; [2]), concrete bridges ([3]; [4]), road pavements ([5]; [6]) or walls and columns ([7]; [8]). This non-invasive technique has one of the highest resolution capabilities achieved in field measurements of these kinds of structures, approaching to few centimetres. However, the combination of resolution and penetration restricts the application of this technique. Penetration increases as the frequency decreases [9]. Higher frequency antennas (between 800 and 2000 MHz) are the most employed in the study of structures and pavements. These antennas present penetrations minor than 1 m under favourable conditions. Notwithstanding, it could be enough in many shallow evaluations. The most restrictive condition to select the antenna use to be the horizontal and vertical estimated resolution. Resolution is usually identified with the capacity of the system to discriminate individual elements embedded in the medium [10]. Horizontal resolution could be considered as the capability to detect lateral changes along a reflector. That is, the capability to detect as two differentiate anomalies two adjacent targets placed at the same depth. Vertical resolution is related to the ability to differentiate in the time axis, two adjacent reflections as different anomalies. These characteristics of the GPR surveys are usually estimated as prior information in order to select the most suitable radar antennas. It is usual to determine approximately the horizontal resolution. In these cases, the electromagnetic characteristics of the medium (dielectric permittivity and conductivity) and the expected depth are used to determine a value of the path, which is considered as the plan resolution (e.g., [11]; [12]). Vertical resolution uses to be considered as the separation in time of two objects equal to a half of the effective pulse duration that is obtained from the width of the signal envelope at its -3 dB level ([10]; [13]). In the literature, several authors present experiments performed in order to determine the horizontal ([14]; [10]) and vertical ([10]; [13]) resolution, comparing the results obtained in specific media to the usual numerical estimations taking into account the properties of the media and the characteristics of the GPR survey.

In this paper we first present two examples of radar data obtained under laboratory conditions in sand in order to determine vertical and horizontal resolution under concrete situation. Three different examples of field data are also included in a second part. These data are obtained in the evaluations of civil engineering structures, and the results are compared to the information obtained from drilling or holes, allowing to determine the resolution achieved in all the different cases.

2 Analysis of resolution under laboratory conditions

GPR Measurements were carried out in sand with a commercial 1.6 GHz nominal centre frequency antenna, manufactured by Mala Geosciences. Different steel bars configuration were embedded in the sand which was characterized by an electromagnetic wave velocity of about 12 cm/ns. Changing the water content of the sand, allows to obtain different wave velocities. Steel bars were buried 3.5 cm in sand. GPR measurements allow to determine the horizontal position of the bars when resolution was available to determine these targets as separated anomalies. Figure 1 shows two different bars configurations, and the radar data obtained in each case (raw and migrated data). These results indicate that, in this particular medium, for depths of 3.5 cm, expected resolution could be about 4 cm that corresponds to a length of 0.4 λ. This estimation was made considering the centre frequency of the spectrum of the received wave (Figure 2), about 1200 MHz that corresponds to a wavelength in this medium of 10 cm. A more complete description of the results and the procedure can be found in [14].

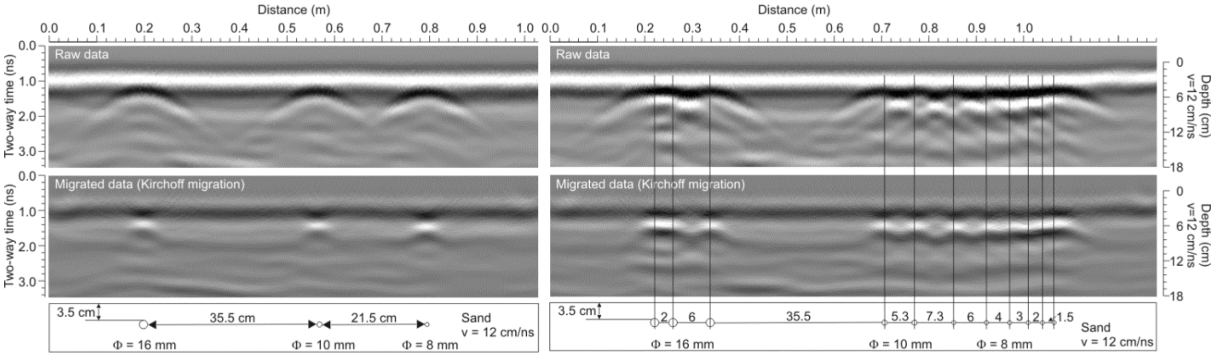

Figure 1. *Raw and migrated GPR data. Bars are differentiate in the case of separation higher than 3 cm (Kirchoff migrated data). Resolution in raw data seems to be about 4 cm.*

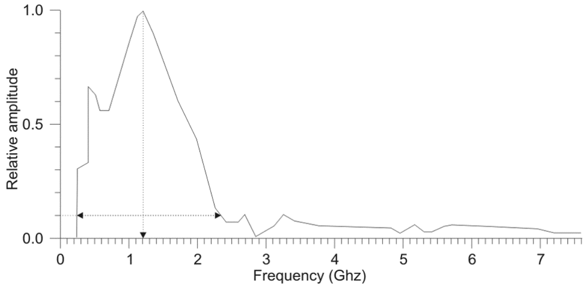

Figure 2. *Frequency spectrum of the reflected wave in sand. Centre frequency is about 1.2 GHz and bandwidth at 3 dB is about 2.1 GHz.*

Vertical resolution was estimated in air, using the configuration shown in Figure 3.

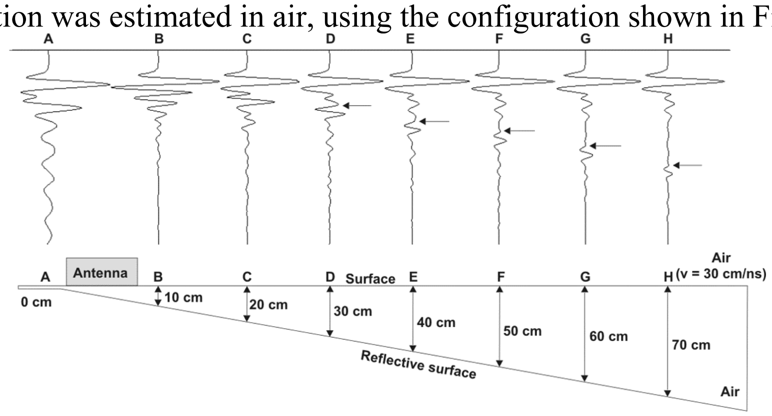

Figure 3. *Vertical resolution in air. Separation between the first surface (wood) and the second surface (metal) higher than 20 cm (1.07 λ) allows to detect both reflections as separated anomalies.*

Radar data was obtained in different positions, changing the distance between the two layers. The upper one was a wood platform, while the second one was a metallic layer. The antenna was moving along the wood platform. Results indicate that the two reflectors can be clearly distinguished when the distance between them is higher than 20 cm, that is, 1.07 λ. This value is similar to the results of Rial et al. (2008) [10] obtained in air with 1 GHz centre frequency antenna and two metal bars, in the case of a distance antenna-bar of 16 cm.

3 Field data results

To compare these laboratory results to the field data, we present several examples of GPR diagrams obtained in different structural survey.

3.1. Reinforced slab

Radar data presented in Figure 4 was obtained in a reinforced concrete base in a parking zone. GPR was applied in order to obtain a complete map of damages (cracks) and moist areas [15]. The average thickness of the slab was 15 cm in the plan. The reinforcement was placed in the bottom of the base, and the distance between bars was 25 cm in plan. No reinforcement exists in the upper part of the slabs. The antenna was 400 MHz nominal centre frequency. The spectrum of the reflected wave presents a centre frequency of about 300 MHz. The measured wave velocity was about 10 cm/ns. Taking into account these considerations, the horizontal distance between bars (25 cm) was 0.75 λ, and the vertical covering distance to the bars (15 cm), 0.45 λ. GPR allows to determine the position of the reinforced bars, to detect cracked zones and the sectors presenting deformation of the slab. In these sections, the vertical distance to the bars was different than 15 cm. Figure 4 shows one of these sectors with a vertical distance of about 11 cm (0.33 λ). GPR also allows to detect changes in the horizontal separation between bars. It is necessary to consider that resolution in concrete structures depends on the nature of the concrete and, specially, on its conductivity [16]. Higher conductivities produce higher attenuation of the wave and increase the difficult to detect as separated anomalies two adjacent targets.

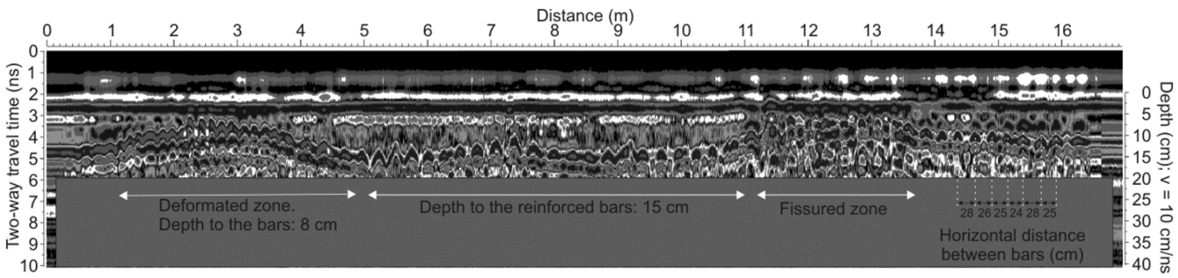

Figure 4. *Radar data obtained in a reinforced concrete slab. Horizontal distance between bars and the vertical distance to the reinforcement were determined.*

3.2. Wet reinforced wall

Figure 5 shows an example of the radar data obtained in a reinforced wall with a 1 GHz nominal centre frequency antenna. The antenna was moved parallel to the base of the wall, at a distance to the floor of about 1.5 m. A wave velocity of about 8 cm/ns was obtained from the hyperbolic records. This velocity corresponds to a relative permittivity of 14. This value is considered characteristic of wet concrete [9], probably presenting high porosity or limestone aggregates [16]. The measured centre frequency is about 620 MHz (Figure 6), corresponding to a wavelength of 12.9 cm. In the radar data of Figure 5, two different levels of reinforcement are detected. The external one is formed by bars with a free distance of about 20 cm (1.55 λ). The deeper one is like a guide for the shallower reinforcement and bars present a separation of about 1 m (7.75 λ) between them. The covering is of about 3.2 cm (0.25 λ). The distance between the internal and the external reinforcement is about 1.6 cm (0.12 λ). Problematic zones are also observed in both extremes of the radar data. In these cases the reinforcement seems to be moved to an incorrect position. Two possibilities could explain the image in both anomalous zones: changes in the position of the reinforced bars, and changes in the GPR wave velocity due to variations in the concrete properties. Even though, later and punctual invasive measurements seem to indicate that the changes in the properties of concrete wall are insignificant. Then, the possible changes of the electromagnetic properties do not explain these noticeable displacements of the anomalies.

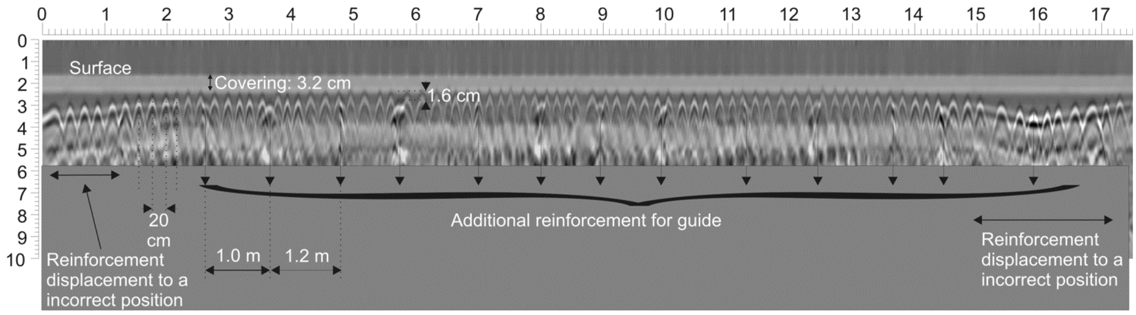

Figure 5. *Radar data obtained in a reinforced concrete wall.*

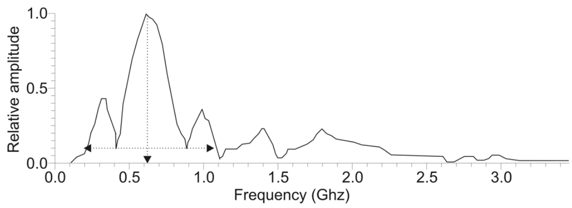

Figure 6. *The centre frequency is near 620 MHz, while the nominal centre frequency is 1 GHz. The bandwidth at 3 dB is about 900 MHz.*

3.3. Study of a historical building

This example was obtained in the evaluation of an historical building, an old palace today partially rehabilitated. This palace was built as a first square tower. Three adjacent houses were jointed to this palace, presenting different constructive structures [17]. The evaluation was carried out with a 1 GHz nominal centre frequency antenna, being the effective centre frequency of about 750 MHz (λ = 13.3 cm). The wave velocity was highly variable due to the different materials used in the supports, but in the shallowest layers an average velocity seems to be 10 cm/ns. GPR survey was applied to the different rooms. In the most conflictive points, invasive drillings punctually allows to determine the exact constructive solution. These invasive evaluations indicate that in one of the studied rooms the floor was supported by old masonry arches and modern reinforced concrete beams (see Figure 7).

Comparing these observations to the radar data (Figure 8) seems to indicate that GPR could determine the bricks that form the arches, and also the reinforced bars inside the concrete beams. These bricks are about 20 cm (1.5 λ) width. Notwithstanding, GPR does not provide enough resolution to determine the different brick, clay, concrete and tiles layers of the most superficial floor. These layers form a 10 cm width coating (Figure 7), but the thickness of each one of the layers is between 1.5 cm (0.11 λ) and 4 cm (0.3 λ).

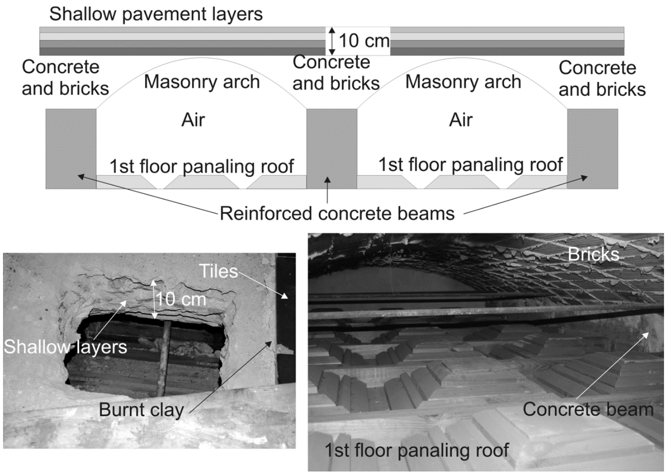

Figure 7. *Scheme of the supports of the floor and photographs of these supports and the most superficial covering layers.*

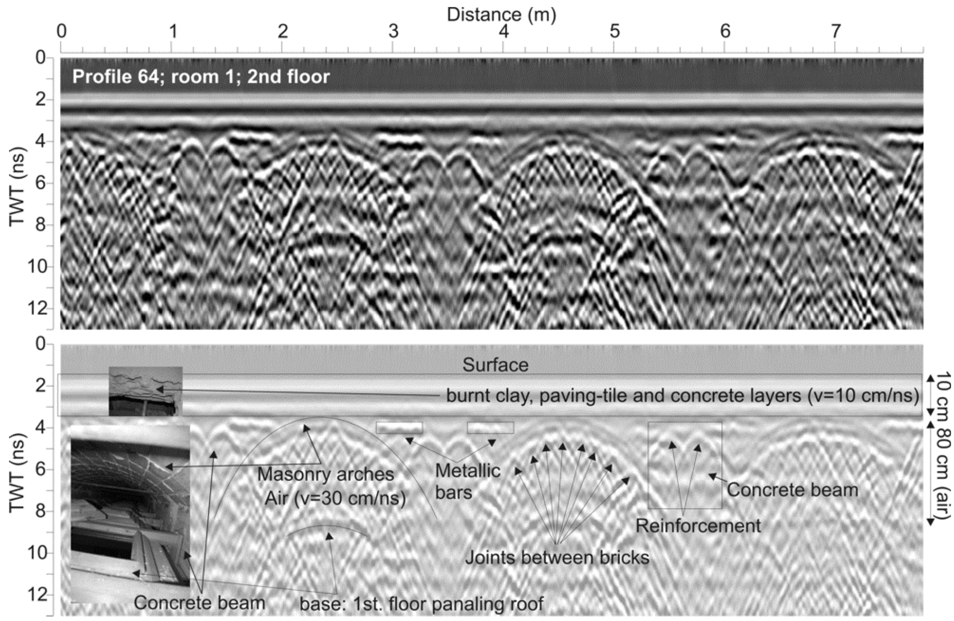

Figure 8. *Radar data showing the different support elements.*

4 Conclusions

In this paper we present some experimental measurements under laboratory conditions and in simple media in order to determine the spatial (vertical and horizontal) resolution provided by GPR. We also show three examples of high resolution evaluations of structures. Two of them are modern structures (a slab and a load wall). The third example is obtained in an historical and old structure, which suffered several remodelling changes. Plain structures (experimental configurations, load bear wall and slab) allow to obtain better resolution than more complex ones (historical building). Also, properties of the different materials affect the final resolution. Notwithstanding, in all the studied cases resolution is enough to obtain accurate and complete images of the structures interior. Vertical resolution approaches to 0.33 λ in the reinforced slab, but multiple and shallow layers in the historical building with thickness corresponding to 0.11 λ to 0.3 λ, are not distinguished and only the existence of a complex 10 cm (0.75 λ) covering could be identified in the radar data. In experimental measurements in air, the two layers were distinguished for distances of about 20 cm (1.07 λ). Referring to the horizontal resolution, experimental measurements provides a value of about 0.4 λ in a 12 cm/ns velocity medium at a depth of 3.5 cm. In the studied cases, radar data allows to distinguish targets separated in 0.75 λ at a depth between 0.45 λ to 0.33 λ (reinforced slab). In the reinforced wall all the elements are clearly separated in the horizontal axis because distances are always higher than λ, and depths are about 0.24 λ. In the historical building, separation between bricks in the vaults is also observed.

Concluding, in the shallow evaluations of structures, horizontal resolution of constructive elements seems to be possible in distances and sizes of about λ. The capacity to distinguish between elements in the vertical axis is possible in cases of depths of about 0.5 λ.

Acknowledgements

This study was partially funded by the Spanish Ministry of Education and Science, project CGL-2005-04541-C03-02/BTE.

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