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Case study on application of ground-penetrating radar for non-destructive assessment of historical building

Ksenija Tešić[1], Ana Baričević[2], Marijana Serdar[3]

[1] *Assistant*, University of Zagreb Faculty of Civil Engineering, *ksenija.tesic@grad.unizg.hr*
[2] *Assistant Professor*, University of Zagreb Faculty of Civil Engineering, *ana.baricevic@grad.unizg.hr*
[3] *Assistant Professor*, University of Zagreb Faculty of Civil Engineering, *marijana.serdar@grad.unizg.hr*

Abstract

Non-destructive techniques such as ground-penetrating radar (GPR) have many benefits for the condition assessment of structures. Acquiring real-time results in a short time frame makes the inspection with GPR very effective even in the case of large areas. The inspection ensures minimal obstruction, therefore, GPR could be beneficial in cases of cultural heritage and historical buildings. By emitting electromagnetic waves into a structure, GPR detects waves reflected from the internal objects. The appropriate analysis and interpretation of results offer information about the position of reinforcement and the presence of possible structural irregularities. The identification of internal degradation due to the presence of voids, cracks, or water intrusion can also reliably be detected by GPR.
In this paper, the main principles of the GPR technique are presented. This is followed by the application of GPR for the localization of reinforcement and determination of slab geometry in the case of Faculty of Teacher Education in Petrinja.

Key words: ground-penetrating radar, non-destructive testing, condition assessment

1 Introduction

Preparation of rehabilitation projects requires data on construction details that are often unavailable due to incomplete or inaccessible documentation. Since these must be determined for the entire structure, it is of interest to use non-destructive techniques (NDT). The advantages of non-destructive testing are the reduction of testing time, the possibility of repeating the test at the same location and, in sum, the lower costs [1, 2]. There are many non-destructive testing methods; however, this paper focuses on the use of ground-penetrating radar (GPR) to evaluate the structure for the rehabilitation project. GPR is a non-destructive technique for structural health assessment that is widely used in civil engineering [3]. It is designed to emit electromagnetic waves into the surrounding material and record reflections from unseen objects [4]. The interest in its use stems from its effectiveness to inspect large areas in a short time in a completely non-invasive way. This type of inspection could be of great importance in historical and heritage buildings where the preservation of structural integrity is a priority [5]. The reconstruction of the waves reflected from the objects determines their presence and position. Moreover, the observation of the wave characteristics can be used to estimate the properties of the host material [6, 7]. However, appropriate analysis requires knowledge and experience in interpreting GPR results.

In this paper, the results of the investigation conducted at the Faculty of Teacher Education of the University of Zagreb in Petrinja using the 2.7 GHz GPR system are presented. Firstly, the principles of ground-penetrating radar are presented. Secondly, the interpretation of the radargrams and the relation of the obtained results with the available project documentation are presented. The GPR was used to determine the location and geometry of the reinforcement in the columns and the concrete slab, as well as with the layers of the mezzanine structure. Furthermore, the results were compared with cover meter and the advantages and limitations of the system for specific cases were shown.

2 Principles of Ground-Penetrating Radar

Ground-penetrating radar (GPR) is based on the emission of electromagnetic waves into the surrounding material to determine the position of objects below the surface. In most cases, it contains a transmitter (T) that emits electromagnetic waves which are then reflected when they hit an object. The reflected wave is registered by the receiver (R), Fig 1a. The recording of a registered wave is also called an A-scan (Fig 1b). The individual recordings are reconstructed into a two-dimensional representation of the examined subsurface, the B-scan or radargram (Fig 1c). On the horizontal axis of the radargram is the position of the GPR and on the vertical axis is the wave travel time (TWT) or depth.

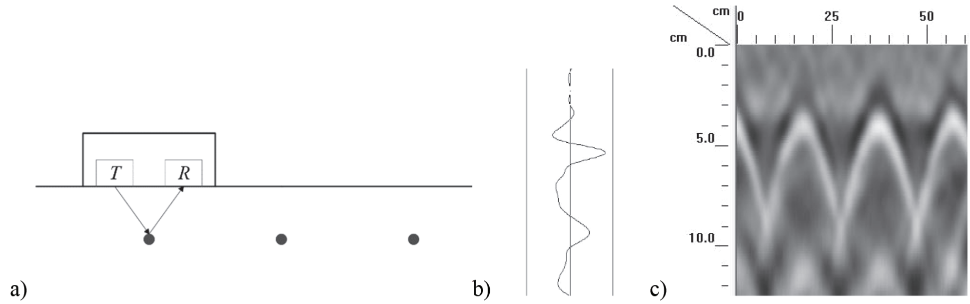

Figure 1. a) GPR system; b) A-scan; c) B-scan or radargram

The radargram is usually a black and white image, with the largest positive values of wave amplitude corresponding to the white areas, while the black areas refer to the parts with the largest negative amplitude values. How much energy is reflected from the object depends on the dielectric properties of the host material and the material of the object; the greater the contrast of dielectric constants between the materials, the stronger the reflection. The fact of high contrast of dielectric properties between concrete and metal is used to locate reinforcement in reinforced concrete structures. When the measurement is made perpendicular to the reinforcement, the rebar is represented as a hyperbola in the radargram. The peak of the hyperbola determines its position.

In fact, the GPR records the travel time of the electromagnetic wave, so that the exact depth of the object depends on the velocity of the wave. Further, the velocity of the wave depends on the dielectric constant (ε_r). The dielectric constant can be assumed based on the material properties (e.g., for dry concrete ε_r=5.5, for wet concrete ε_r=12.5 [8]), determined for a known depth, or assumed based on the properties of the hyperbola.

The penetration depth of the signal is limited. It mainly depends on the central frequency of the transmitting antenna. As the frequency increases, the penetration depth decreases. Antennas used for condition assessment of structures are usually in the range of 1 GHz - 2.5 GHz [9], where a 2 GHz antenna has a penetration depth of 0.5 m [10].

3 Experimental investigation

3.1 Data collection

The Faculty of Teacher Education of the University of Zagreb is located at Matica Hrvatska Square in Petrinja, Croatia, Fig 2. The main objective of the study was to determine the location of reinforcement in the concrete columns, layers and the geometry of the mezzanine structure, as part of the seismic vulnerability assessment.

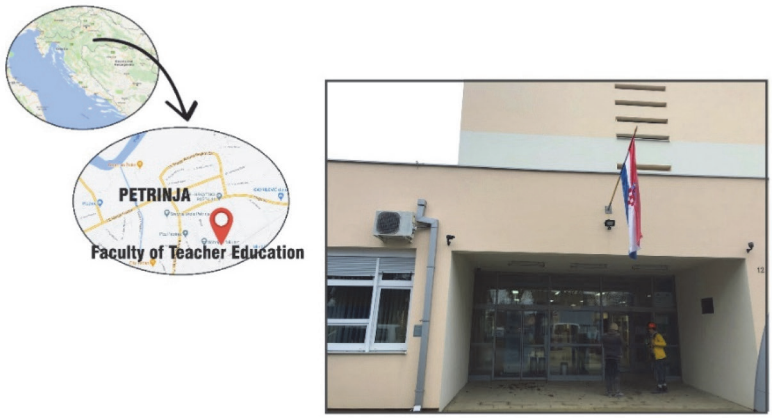

Figure 2. Faculty of Teacher Education in Petrinja, Croatia

The GPR survey was performed using the ground-coupled handheld GSSI Structure Mini XT system with a centre frequency of 2.7 GHz, Fig 3a. Profiles were performed along the longitudinal axis of the columns to locate the stirrups (profile 1), while perpendicular profiles were used to locate the longitudinal bars (profiles 2 and 3), Fig 3b. Data collection was performed for 10 columns.

The survey of the mezzanine structure between the ground and first floor was conducted without removing the parquet flooring. According to the project documentation, the mezzanine structure consists of the following layers: parquet, cement screed, bitumen and ribbed concrete slab. The profiles (profiles 4 and 5) were taken in two perpendicular directions, Fig. 3c. In addition, the mezzanine structure was examined from the underside with two profiles, Fig. 3d. Profile 6 was taken from the underside of the concrete slab, while profile 7 was taken from the side along the rib of the ribbed slab. Although profiles 4, 5, 6, and 7 were not from the same part of the slab, it was assumed that the geometry of all slabs in the building was the same. The GPR profiles were further analysed in Radan 7 software. The dielectric constant of 5.5 was determined from a known depth verified at the site. This value was assumed to be constant for each scan considered.

The results obtained with GPR were compared with a cover meter manufactured by Proceq, Switzerland.

Figure 3. a) GPR handheld system; b) Column profiles; c) Profiles from the top of the mezzanine structure; d) Profiles from the underside of the ribbed concrete slab

3.2 Results and discussion

The GPR system was able to obtain information about the position and number of stirrups and longitudinal bars in the columns. The profiles obtained from the GPR results and the scheme of the reinforcement in the column are shown in Fig 4. The position of the rebars is determined using the peak of the hyperbola, while their spacing is determined using the spacing of the peaks. The position of all rebars was confirmed using the cover meter.

In the case of one column, the GPR system showed no detectable hyperbola in the scan, Fig 5a. The results were checked with the cover meter and conflicting results were found. The cover meter successfully located stirrups and longitudinal bars. The column was then opened and a steel wire mesh was found nearly 1 cm from the surface, Fig 5b. The authors hypothesize that the steel wire mesh prevented the signal from penetrating deeper into the material, obscuring the reinforcement of column.

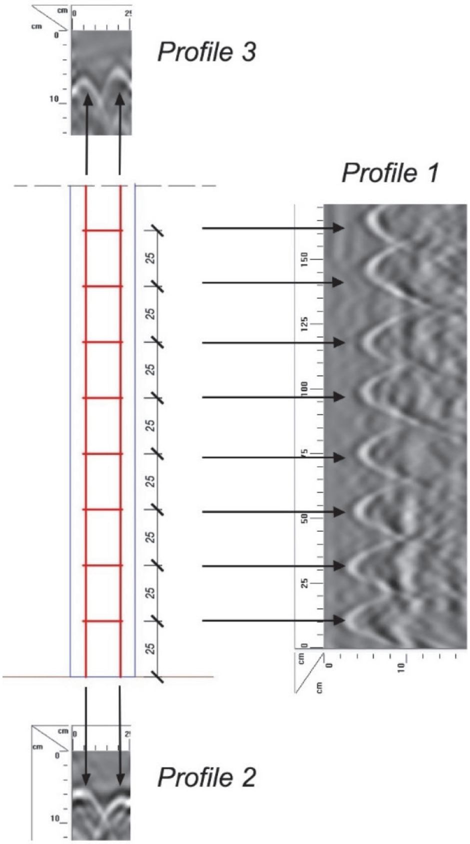

Figure 4. Scheme of the column reinforcement

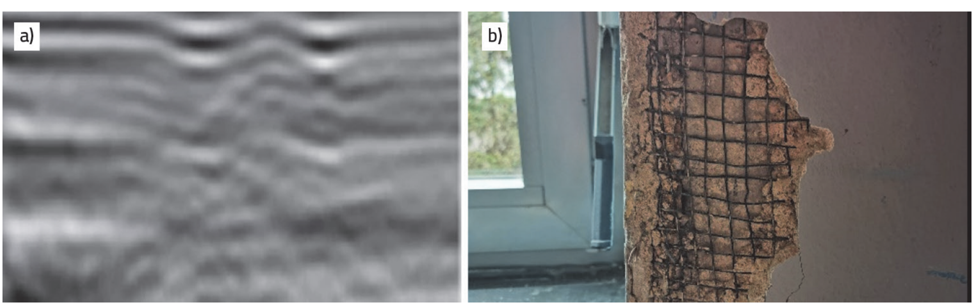

Figure 5. a) GPR profile above steel wire mesh; b) Steel wire mesh

Contrary, in a number of cases where the plaster thickness was very high (≈ 5 cm), the cover meter was unable to locate the reinforcement in the columns. This may be related to the fact that the measuring device cannot detect reinforcement placed ≥ 7 cm below the testing surface. In these cases, measuring the cover depth with the cover meter was insufficient. In contrast, the GPR was very effective in these cases and showed the advantage over the cover meter.

The profiles obtained on the top of the slab are shown in Fig 6 (profile 4) and Fig 7 (profile 5), while the reinforcement plan from the project documentation can be seen in Fig 8. The geometry corresponds to the ribbed slab. The possible representation of the geometry from the GPR results is shown below. The first 8 centimetres correspond to the layers of the floor. The top of the concrete slab was shown as a line on the radargram. The thickness of the slab was estimated to be approximately 6 cm. Detected hyperbolas in the slab on the radargrams were assumed to be the rebars. At the end of the rib there were two reflections nearly 8 cm wide that could correspond to the top and bottom edges of the wooden plank. The presence and geometry of the planks were confirmed in the rib, Fig 3d.

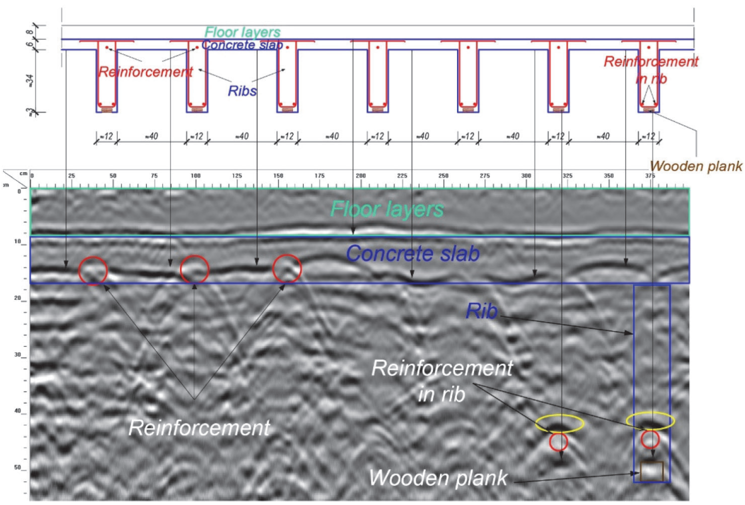

Figure 6. Possible representation of geometry slab from the profile 4

Positive hyperbolic signs from reinforcement in the ribs were noted above the wood plank. Although the project documentation (Fig 8) states that these should be two hyperbolic marks from two reinforcing bars in the rib, it could be possible that they are close together so that the GPR could not detect them as separate objects. Also, in Fig. 6, the authors found negative signs circled in yellowed above the rebars in the rib. These are the locations where the nails connect the wood plank to the rib, and it is possible that the concrete was improperly poured at this location. It could be possible that there is significant segregation so the mark could be from the air void space. Evidence of improper casting of the ribs was confirmed on site, Fig 3d.

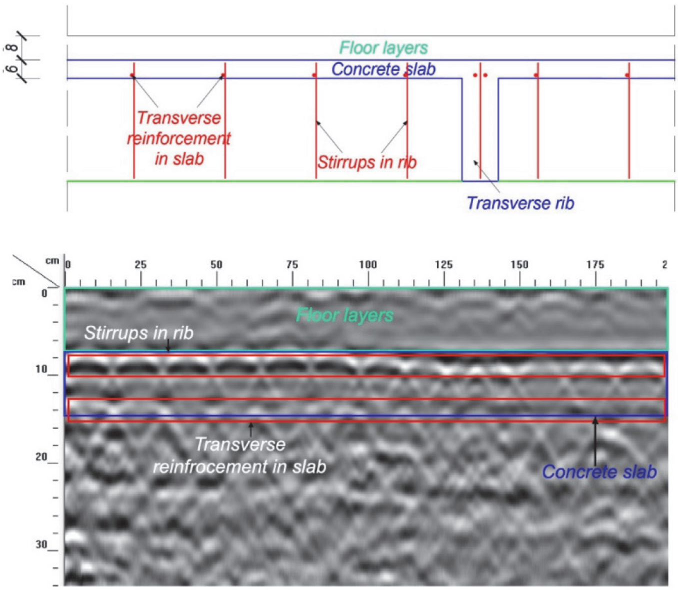

Figure 7. Possible representation of geometry slab from the profile 5

The possible representation of the geometry of the slab from profile 5 is shown in Fig. 7. It was noted that the profile was most likely obtained between two adjacent ribs, but closer to one of them, so that the profile lies just above and perpendicular to the legs of the stirrups in a rib. Two arrays of hyperbolas were found in the radargram. The first is most likely from the legs of the stirrups in the rib, while the second is from the transverse reinforcement in the slab. The interpretation problems arose from the fact that the rebars are close to the top and bottom concrete surfaces, so they overlap with these reflections. The determined spacing between these hyperbolas is 15 cm, which is not consistent with the project documentation. Therefore, the spacing of the stirrups and the transverse reinforcement in the slab was checked by the profiles 6 and 7, Fig. 9.

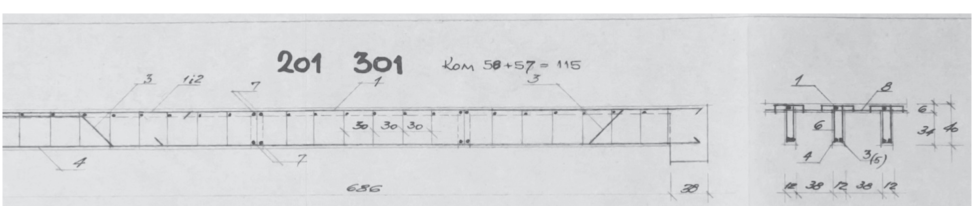

Figure 8. Reinforcement plan

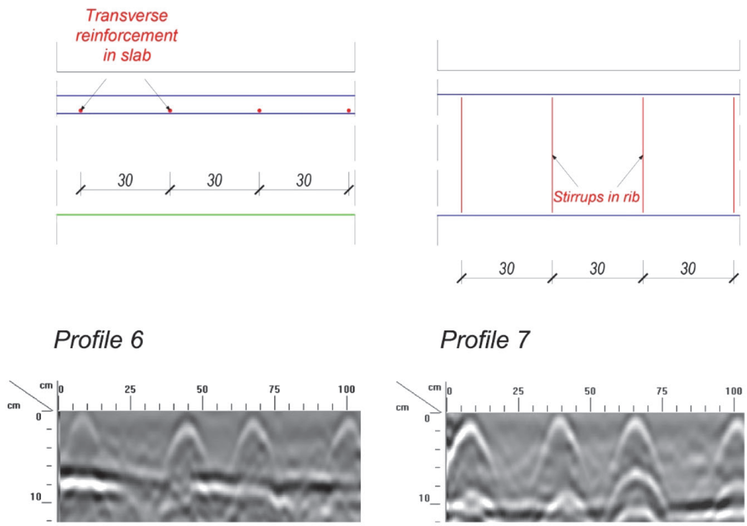

Figure 9. Scheme of the stirrups in rib

It was confirmed that the distance is 30 cm, as in the project documentation. Therefore, the spacing of 15 cm could be explained by an additional transverse reinforcement in the slab at the level of the legs of the stirrups, located in the middle of two adjacent stirrups. Also, an additional transverse reinforcement may be embedded in the second reinforcement array at a spacing of 15 cm. The slab was not opened, therefore the representation of the concrete slab in the direction parallel to the ribs is not fully illuminated.

4. Conclusions

In this study, the GPR proved to be an effective tool in the rehabilitation project of existing structures. The system was able to locate the position of reinforcement in columns in a short time. The only limitation of the GPR system was in cases where the steel wire mesh in the column prevented the signal from penetrating the concrete. Here, GPR was unable to detect the reinforcement and the cover meter showed the advantage over GPR. In contrast, GPR was able to locate reinforcement with thick concrete cover compared to the cover meter. GPR was also used to determine the geometry of the concrete slab. Difficulties were encountered in complicated structures with a high number of reflections, so interpretation was not straightforward.

Acknowledgements

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