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USING AND MODELING GROUND PENETRATING RADAR ON DENSELY REINFORCED SLABS

Abstract

Ground Penetrating Radar - GPR by modern equipment has grown in importance in recent years in non-destructive testing. Estimating steel rebar position and diameter is the main focus for assessment of existing reinforcement concrete facilities. This paper presents the latest modern non-destructive technique – suitable for testing reinforcement concrete members. The capabilities of this technique for locating reinforcement bars in unilaterally accessible, densely reinforcement slab are described.

Keywords: Densely reinforcement slab, ground penetrating radar, stepped-frequency wave GPR

ПРИМЕНА И МОДЕЛИРАЊЕ ГЕОРАДАРА НА ГУСТО АРМИРАНИМ ПЛОЧАМА

Сажетак

Испитивање бетона георадаром у последњих неколико година је добило на значају у односу на примену осталих метода без разарања. Мерење положаја и пречника шипки су основни фактори за процену стања постојећих армиранобетонских објеката. У раду је приказана примена ове недеструктивне методе са модерном опремом за испитивање армиранобетонских елемената. Приказане су могућности лоцирања положаја шипки арматуре на густо армираним плочама чија је само једна страна доступна за испитивање.

Кључне ријечи: Густо армиране плоче, георадар, stepped-frequency continuous wave GPR

1. INTRODUCTION

Ground penetrating radar (GPR) is a non-destructive technique with a wide range of potential applications in the testing of concrete structure. Large part of domestic industrial facilities and infrastructure was built between 1960–1980. The most of them have unknown rebar spacing, cover and diameter due to the non-availability of their structural drawings. Information on rebar diameter, spacing and cover depth is essential in determining the structural capacity. It is gaining acceptance as a useful and rapid technique for non-destructive detection of inhomogeneities and the types of other defects, which can occur in reinforced concrete elements. When evaluating structural integrity or carrying out retrofits in concrete structures, it is also important that you detect embedded objects.

The operating principle of GPR is based on detecting discontinuities of dielectric properties that are caused by one or more targets at different depths and orientations within the object under investigation. At the boundaries of such discontinuities, electromagnetic energy is partially transmitted through the targets and partially reflected in various directions, among which also towards the surface of the object [1].

Most GPR consist of three components: a console, an antenna, and an encoder. The first two are mandatory. The console is the brains of the system. This data logger communicates with both the encoder and the antenna to initiate a signal and record the responses. The antenna is where the GPR signal is produced.

The main advantages of GPR are: its fast data acquisition capability, its high resolving ability and the fact that it responds equally well to metallic and nonmetallic targets. Its main drawback is the complex nature of its data and the difficulty that the GPR user faces when trying to interpret them. Interpretation of the data acquired using a GPR is often a complicated and error-prone procedure, mainly due to the complexity of the GPR signals and the variety of factors that influence and determine them [2].

The dielectric properties of the object determine the speed of the electromagnetic waves within it. This enables the user to estimate the absolute depth of the reflecting targets. Precise speed estimation depends on knowledge of tabulated values of dielectric properties, such as those of wet or dry concrete.

Estimated depths and locations are then graphically represented in 2D or 3D views. Further physical effects within the object itself, its embedded targets and their interfaces, such as attenuation, scattering, and losses, affect the signal strength adversely. The strength of some of these unwanted effects depends on the frequency of the transmitted electromagnetic wave.

2. PHYSICAL PRINCIPLES AND THEORY

GPR principles are based on the electromagnetic (EM) theory where the physics of the EM field propagation is described by Maxwell's equations and material properties are quantified by constitutive equations. As a combination of these two factors, the GPR signal is an output that provides information about the properties and configuration of the subsurface [3].

The propagation of the EM waves depends on the three main EM properties of the host material: the dielectric permittivity ε, the electric conductivity σ and the magnetic permeability μ. The dielectric permittivity and the electric conductivity are strictly related to the EM wave features. ε affects the wave velocity, and σ controls the wave attenuation. On the contrary, the magnetic permeability μ does not relate to the propagation of the wave for all the non-magnetic materials, as it is equal to the free-space magnetic permeability μ_0. On the other hand, the main factors affecting the penetration depth are the frequency of the emitted signal (for structural inspections, antennas with central frequencies above 1 GHz are used) and the type of material investigated [3,4].

Theoretical background of EM fields is described by Maxwell's equations as follows:

$$\nabla x E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla x H = J + \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla \cdot D = q \tag{3}$$

$$\nabla \cdot B = 0 \tag{4}$$

where E is the strength vector of the electric field (V m^{-1}); q the electric charge density (C m^{-3}); B is the density vector of the magnetic flux (T); J is the density vector of the electric current (A m^{-2}); D is the electric displacement vector (C m^{-2}); t is the time (s); and H is the intensity vector of the magnetic field (A m^{-1}).

Material properties are instead quantified by the following constitutive relationships:

$$\mathrm{J} = \sigma \cdot E \tag{5}$$

$$\mathrm{D} = \varepsilon \cdot E \tag{6}$$

$$\mathrm{B} = \mu \cdot H \tag{7}$$

Combination of the EM fields' theory and the material properties allows to describe comprehensively a GPR signal.

The speed of propagation of electromagnetic waves in a different environment is:

$$\mathrm{v} = \frac{1}{\sqrt{\varepsilon_0 \cdot \varepsilon_r \cdot \mu_0 \cdot \mu_r}} = \frac{c}{\sqrt{\varepsilon_r \cdot \mu_r}} \tag{8}$$

For materials where the radar method is applicable, it can be assumed that m≈ 1 (in ferromagnetic materials this is not valid but ferromagnetic materials can not be investigated with the radar method):

$$\mathrm{v} = \frac{c}{\sqrt{\varepsilon_r}} \tag{9}$$

This means that the signal velocity within materials is mainly defined by their relative permittivity. For practical purposes, it can be assumed that dielectric constants of materials are in the range between 1 (air) and 84 (water) which leads to signal velocities between 3×10^8 m s−1(air) and 0.33×10^8 m s−1(water).

The high velocity of the radar signal is responsible for one of the main advantages of the radar method. As the signals travels with such a high velocity, a single measurement takes very little time and therefore the number of measurements per second is, from a physical point of view, almost unlimited [5,6].

Reflection coefficient R is:

$$\mathrm{R} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \tag{10}$$

If an electromagnetic wave hits an interface, part of the energy will be transmitted and part will be reflected. For a plain electromagnetic wave in a low loss material hitting at vertical incidence an interface between two materials with e_1 and e_2, the reflected wave can be described as:

reflected wave = R × incident wave

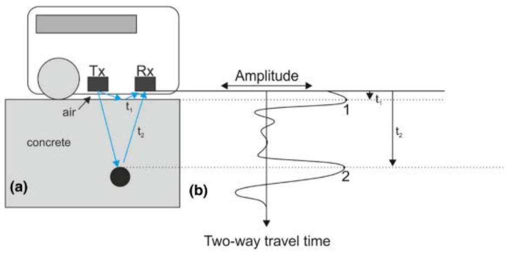

Figure 1. *Layout of a survey on a reinforced concrete structure using a ground-coupled GPR system, b corresponding GPR signal output*

The usual maximum penetration depth in concrete is about 60-65cm. However, it may not always achieve maximum penetration. Water in concrete is the biggest contributor to electrical conductivity. Generally, the wetter concrete has the higher its electrical conductivity, and the penetration will be worse [7].

The size of the required target affects the strength of the returning GPR wave. Larger targets that present a greater cross-section return more GPR wave energy to the receiver.

Typically, three visualisation modes can be listed for a GPR signal that provide three different levels of information: an A-scan (Figure 1), a single radar trace along the depth axis; a B-scan, a set of sequential single radar traces collected along a specific scanning direction; and a C-scan, a set of B-scans extrapolated at a certain spacing along the depth axis.

3. STEPPED-FREQUENCY CONTINUOUS WAVE GPR

Radar imaging is performed by transmitting an impulse of electromagnetic energy, which is then followed by capturing its echoes. Characteristics of an object being observed are extracted from these echoes, which contain useful information, such as range, speed, and reflectivity of the object. Instead of transmitting an impulse directly in the time domain, stepped-frequency continuous-wave (SFCW) radars synthesize the impulse in the frequency domain. Since a time, recent innovations in the field of structural GPR now enable us to largely resolve the long-standing trade-off between resolution and penetration depth.

Proceq GPR Live uses SFCW technology, i.e. it continuously broadcasts electromagnetic waves and gathers data from the reflected component of the waves in the frequency domain. Until recently, the time-consuming calculations associated with the real-time inverse Fourier transforms in SFCW systems limited its application.

Proceq GP8800 equipment is used (Figure 2). Features the unique implementation of SFCW radar technology by Proceq, is delivering the most ultra-wide bandwidth ever in a handheld GPR device. The Proceq GPR Live app connects to the Proceq GP8800 probe and runs on any recent iPad, bringing concrete imaging to your eyes through crisp and high-resolution. Proceq GP8800 features the unique implementation of SFCW radar technology by Proceq, delivering the most ultra-wide bandwidth ever in a handheld GPR device.

Thanks to faster processing capabilities available nowadays, this limitation no longer applies to GPR. Additionally, through electronics design optimization, the maximum signal acquisition time has more than doubled compared to traditional GPR systems, as shown in the next section. Effectively, this enables a longer period during which signals can be gathered with a high signal-to-noise ratio from deeper within the object. Moreover, instead of operating using pulses centred around a single nominal frequency, it relies on multiple frequency steps with a transmitter frequency response that corresponds to the full range of modulated frequencies between 0.4 and 6.0 GHz.

Figure 2. *Proceq GPR Live 8800*

In a more realistically representative setup with the system fully coupled to a concrete structure, an ultra-wide net component between 1.0 and 3.5 GHz has been established to be practically available in the field, and immune to lower and higher frequency noise effects.

These technological features provide a distinct advantage compared to traditional GPR devices: target detection is now possible with a higher accuracy, without the need of a priori expectations of what could be detected and at which depths within the object. Additionally, the received data is processed by the onboard electronics and then visualized in 2D and 3D using a tablet.

Maximum depth range is about 65 cm in dry concrete. Measurement modes include line scan mode and area scan mode with flexible grid.

4. NUMERICAL MODELLING OF GPR

Modelling of GPR responses – either analytically or numerically – plays a central role in advancing our understanding of GPR as well as providing the means for testing new data processing techniques and interpretation software.

Most of the proposed approaches are based on the finite difference time-domain (FDTD) method. The main reasons for such widespread use of the FDTD method are: its ease of implementation in a computer programme – at least at a simple introductory level – and its good scalability when compared with other popular electromagnetic modelling methods such the finite-element and integral techniques.

The availability of a free GPR modelling tool gives both researchers and practitioners the opportunity to numerically ‘‘experiment’’ with GPR on their computers without incurring a substantial cost by creating expensive physical models – at least at an initial stage of a project. Simulating what-if scenarios can save money and time as well as provide data to support project proposals that could employ GPR but need some preliminary evidence in order to convince more sceptic project managers of GPRÕs suitability to solve a given problem. Most importantly however, a freely available and well documented modelling tool avoids the syndrome of re-inventing the wheel that plagues many new research efforts that need GPR modelling facilities.

All electromagnetic phenomena, on a macroscopic scale, are described by the Maxwell's equations. The FDTD approach to the numerical solution of Maxwell’s equations is to discretize both the space and time continua. Thus, the spatial and temporal discretization steps play a very significant role since the smaller they are the closer the FDTD model is to a real representation of the problem [8,9,10].

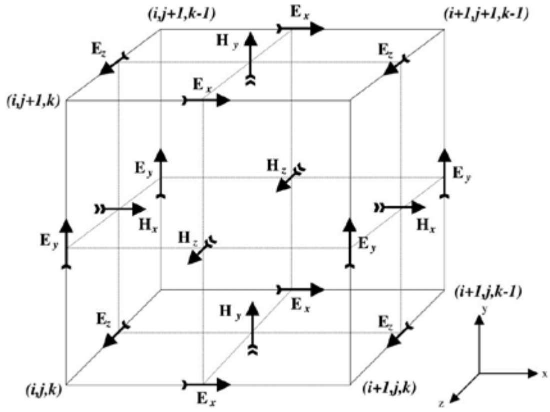

Figure 3. *Yee cell.*

The FDTD model represents a discretized version of the real problem and of limited size. The building block of this discretized FDTD grid is the Yee cell named after Kane Yee who pioneered the FDTD method [11]. The 3D Yee cell is illustrated in Figure 3. The 2D FDTD cell is easily obtained as a simplification of the 3D Yee cell [11].

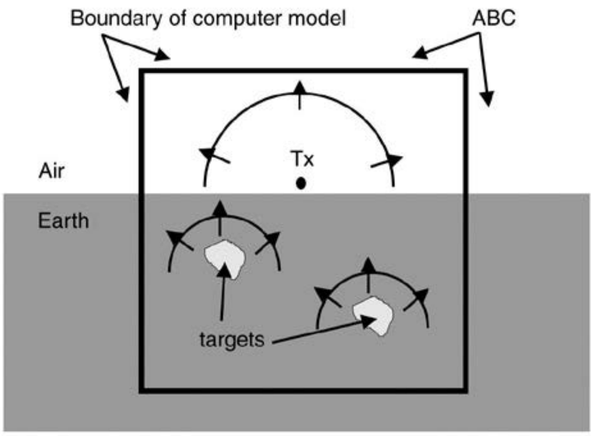

Figure 4. *FDTD view of the model’s space*

Figure 4 illustrates the basic difference between a real problem’s space and the actual FDTD modelled space. In Figure 2 it has been assumed that the half-space, where the target is situated is of infinite extent.

GprMax2D is a computer program that implements the FDTD method for GPR modelling in 2D. GprMax2D uses a simple ASCII (text) file to define the model’s parameters. In this file special commands are used which instruct the software to perform specific functions that are required by the type of the model the user wants to create. Some of the commands of GprMax2D are shown in Table 1.

Table 1.Some of GprMax2D commands

Command	**Function**
#domain:	Controls the physical size of the model
#dx_dy:	Defines the discretization steps

#time_window:	Defines the simulated time window for the GPR trace
#medium:	Introduces the electrical properties of different media in the model
#box:	Introduce a rectangle of specific properties into the model‘s space
#cylinder:	Like the box: but introduces a cylinder into the model
#triangle:	Like the box: but introduces a triangular patch
#tx:	Specifies the details of a transmitter (Tx)
#rx:	Specifies the details of a receiver (Rx)
	Defines the simulated time window for the GPR trace
#scan:	Can be used to automatically generate B-Scans

The flexibility of GprMax2D allows the modelling of complex what-if scenarios. In the following a simple example of modelling rebars in concrete is presented. The geometry of the problem consists of a 2 m wide slab, where rebars of 32 mm diameter are located at an average depth of 150 mm from the slab surface. Although, the horizontal distance between each rebar is fixed at 100 mm, their cover depth is randomly varied between ±4 mm from the average cover depth of 150 mm.
An illustration of the model’s geometry is presented in Figure 5:

```
#title: B-scan from a steel rebars buried in a dielectric half-space (concrete)
#domain: 0.740 0.280 0.002
#dx_dy_dz: 0.002 0.002 0.002
#time_window: 5.5e-9
#material: 7 0 1 0 half_space
#waveform: ricker 1 3.5e9 my_ricker
#hertzian_dipole: z 0.200 0.240 0 my_ricker
#rx: 0.240 0.240 0
#src_steps: 0.003 0 0
#rx_steps: 0.003 0 0
#box: 0 0 0 0.740 0.240 0.002 half_space
#cylinder: 0.30 0.150 0 0.30 0.150 0.002 0.032 pec
#cylinder: 0.42 0.150 0 0.40 0.150 0.002 0.032 pec
#cylinder: 0.54 0.150 0 0.50 0.150 0.002 0.032 pec
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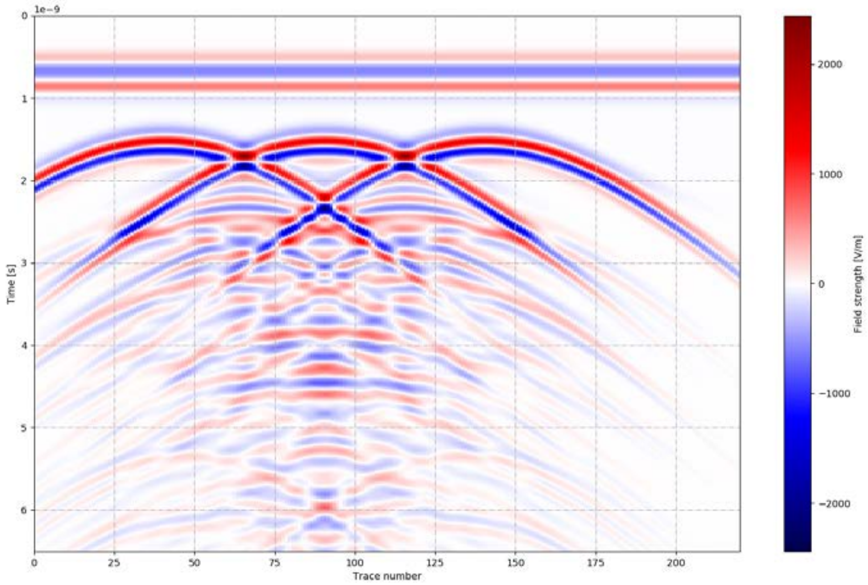

Figure 5. *Simulated GPR scans from the 2D concrete slab model*

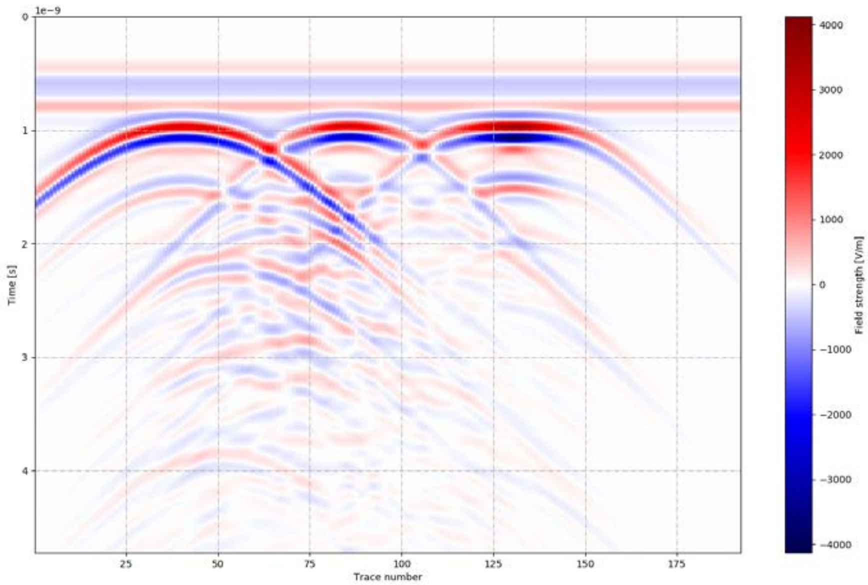

Figure 6. *Simulated GPR scans with reduced cover depth*

The horizontal distance between rebar remained the same and cover depth is reduced from 150 mm to 50 mm. The changed model is shown on Figure 6. It can be clearly noticed that the changed value of cover depth is approaching the threshold where clearly expressed results are lost.

5. EXPERIMENTAL EXAMPLE

The aim of experimental example was focused on densely reinforced elements. The subject of testing was deck slab of the bridge 11 in Lot 4 Ring road over Belgrade (Figure 7). The bridge deck slab is designed as a full deck slab facilitated with Styrofoam. The upper and lower zone of the deck slab is heavy reinforced with 32 mm diameter bars. In the transverse sense, 9 rows of Styrofoam rollers were installed. The rollers are 90 cm in diameter and the axial distance between the rollers is 130 cm (Figure 8 and 9).

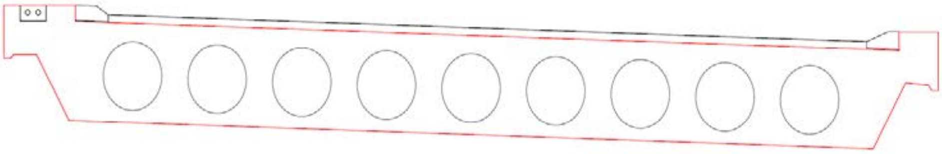

Figure 7. *Cross-section of decking slab*

Figure 8. *Deck slab*

Figure 9. *Deck slab reinforcement*

To keep the styrofoam rollers at the projected position, the Contractor has installed 2 cm wooden slats along the extensions. A reinforcement mesh was laid over the rollers thus formed. The reinforcement mesh is tied to the installed reinforcement, which prevents the movement of the Styrofoam rollers.

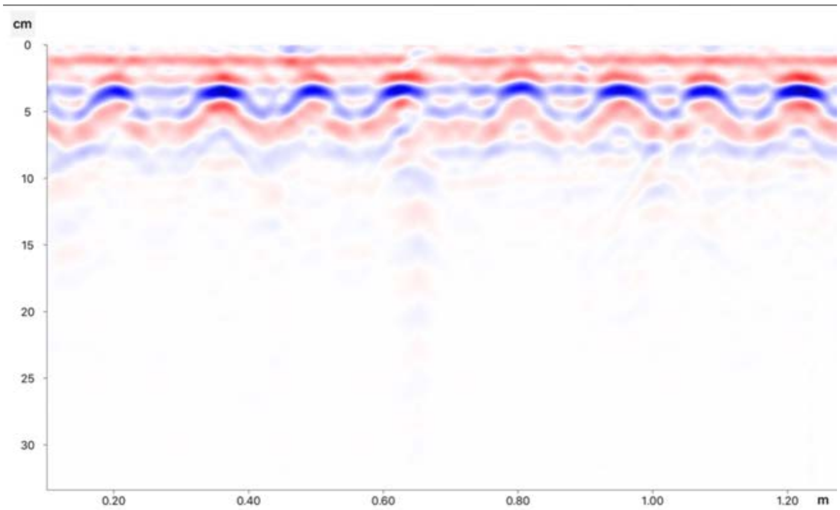

Figure 10. *GPR live line scan*

Proceq GPR Live GP8800 were used (Figure 10 and 11). As can be seen on figures, heavy and densely reinforced bars have been successfully identified. The aim of the experimental work was to investigate the possibility of scanning large diameter reinforced bars at a clear distance of 10-12 cm. GP8800 makes clear that it is possible to compare software modelled and in-situ scanned data.

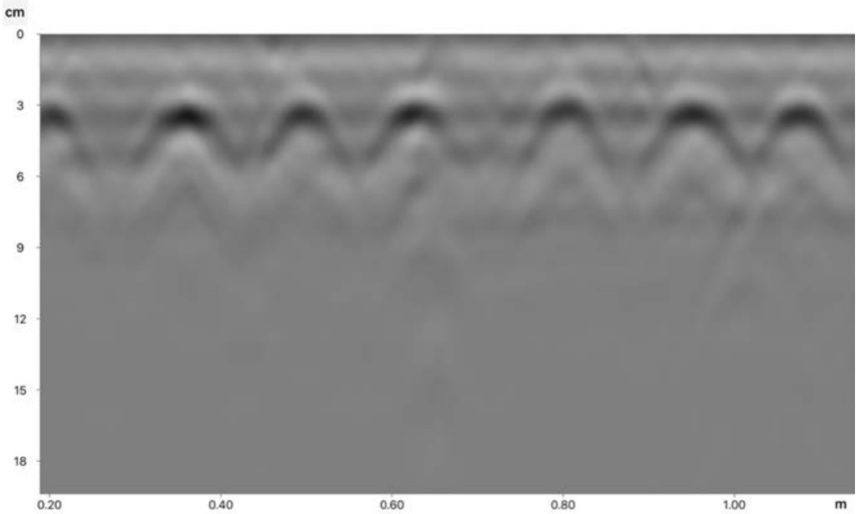

Figure 11. *GPR live line scan - radargram*

6. CONCLUSIONS

Non-destructive technique of GPR has been successfully implemented to detect the foreign entities and anomalies in concrete elements. Using this approach, it has been possible to monitor the various type of defects or eliminate doubt that something has not been performed according to the technical documentation.

Numerical modelling of GPR is very useful in enhancing our understanding of the GPR detection mechanism. The GprMax suite of programmes allows the simulation of realistic scenarios encountered in everyday use of GPR. As computer power is constantly increasing GPR modelling will become an important tool in training new GPR users as well as improving data interpretation of complex GPR sections.

The presence of steel rebars, which were covered with the concrete layer, could be detected clearly with ease and this is noticeable. The position of rebar from the top surface is seen at 30-50 mm in the depth profile of concrete element. Two layers of rebar could also be detected. It can be seen in the form of triangular shaped ripples separated by the second black thick strip.

GPR provides an efficient and versatile means for detecting rebars in the reinforced cement concrete slabs in rigid pavements along with their real depths and rebar array dimension. Single layer and double layer rebars have been successfully detected due to the use of advanced hardware and software features of the system being used.

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