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Evaluation of the Iron State in Humid Zones Using GPR with 1.6 GHz Bowtie Antenna

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This report offers a study of iron status in moist zones using a 1.6 GHz Ground Penetrating Radar (GPR). The latter is a geophysical prospecting tool that analyzes the propagation, refraction, and reflection of high-frequency electromagnetic (EM) waves (from 300 MHz to 2.3 GHz). To replicate GPR signals, we used the GPRMAX program, which allowed us to model the soil's electrical and magnetic properties as well as the GPR itself. Several models were created to replicate various geological situations. The simulation began with a rectangular block as the starting model. The first and second models are basic profiles that illustrate the propagation of an EM wave. The third model is used to investigate the propagation of EM waves (reflected waves) in dry and wet concrete in order to demonstrate the influence of moisture on EM waves. To simulate different properties of a dielectric medium, a set of models was built. We simulated several different physical media using a finite difference time domain (FDTD) approach, which is the method on which the scientific calculation code of the GPRMAX simulation program is based. When a radar signal propagates through an environment, the presence of hyperbolas indicates the presence of buried objects.

Keywords: Ground penetrating radar (GPR), Bow-tie antenna, GPRMAX, FDTD, Geophysics.

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1. INTRODUCTION

Ground Penetrating Radar (GPR) [1, 2] is a fast, non-destructive investigation system for the near subsurface based on the reflection of electromagnetic (EM) waves. With this technique, it is possible to measure the contrasts, electrical properties, and materials of the subsurface to draw conclusions about their nature and distribution. It allows us to image the subsurface at depths ranging from several meters to several kilometers, depending on the frequency range. From the surface, GPRs generally operate in a frequency range of a few MHz to a few GHz. They are now used in many fields such as geology and civil engineering [3, 4].

The study presented in this paper is a theoretical investigation of EM wave propagation in heterogeneous environments (ground penetrating radar application) [2]. The propagation of an EM wave is determined by the following three parameters: electrical conductivity σ, electrical permeability ε, and magnetic permeability μ. In geological environments, these parameters are complex and vary with frequency. To simulate the GPR and the propagation of EM waves, a numerical code based on the finite difference time domain (FDTD) method has been developed which provides the possibility to simulate the geological radar (GPR) in the chosen medium [5]. FDTD modeling allows the resolution of Maxwell's equations in a space consisting of a series of cells in which properties of the medium are constant. The concept of dividing the space into discrete elements allows the study of complex situations due to both their geometry and the variety of properties of the media used. Also, the finite differences allow to achieve any degree of precision. It is enough to reduce the size of the cells and increase the resolution of the mesh until the desired precision is achieved [5].

2. THEORETICAL BACKGROUND

The antenna remains an important part of the GPR system. It establishes the link between the device and the propagating medium. A radar always requires the use of an ultra-wideband antenna. This means that it maintains the same impedance, directivity and polarization properties over a wide frequency range. As a bowtie antenna is an ultra-wideband antenna, so it has been used in this proposed work.

2.1 Bowtie Antenna

A bowtie antenna consists of a triangular metal plate with the feed at the apex. It is used in many applications, such as GPR and mobile stations. A bowtie antenna can be printed on a substrate with each arm placed on either the top or bottom of the substrate. Feeding of such a structure is done by designing suitable strip lines which are connected to a coaxial feed placed on one of the edges of the substrate [6].

This type of antenna has reflections at its extremities. A common method to further increase bandwidth and avoid multiple reflections is to place resistive loads on both sides of the antenna which improves bandwidth and prevents ringing effects. However, this is done at the cost of a lower yield.

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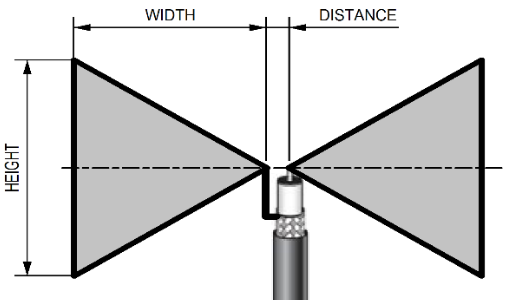


Fig. 1 – Bowtie antenna geometry

2.2 Design Methodology

A traditional bow-tie antenna (TBT antenna) has been designed to cover the entire UWB range, using CST simulation tool, with a shape and optimized dimensions as shown in Fig. 2 by feeding it with a discrete port having an impedance of 300 Ω [14].

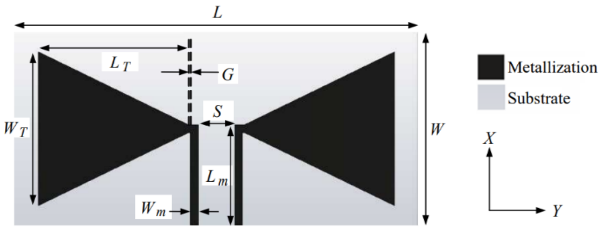


Fig. 2 – Geometry of the TBT antenna

The structural parameters of the designed antenna are $L = 520$ mm, $L_T = 188.8$ mm, $L_m = 136$ mm, $W = 240$ mm, $W_T = 192$ mm, $Wm = 10.4$ mm, $S = 46.4$ mm, $G = 3$ mm, dielectric FR4 substrate of 1.6 mm thickness, relative permittivity (ε_r) of 4.3, and dielectric loss tangent of 0.025. The simulated reflection coefficient S_{11} of the TBT antenna is shown in Fig. 3 which indicates broad operating bandwidth over the intended frequency range.

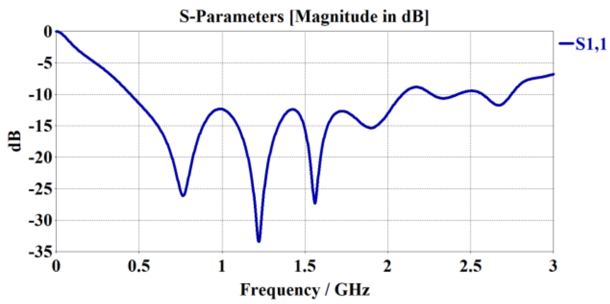


Fig. 3 – Simulated return loss versus frequency for the TBT antenna

2.3 Reflection Coefficient

Any EM wave can be reflected in whole or in part. To quantify the reflection, a coefficient is used, the reflection coefficient. The reflection coefficient quantifies the change in amplitude that the EM field experiences when it encounters an interface between two materials. Namely, when an EM wave encounters a boundary between two materials with different physical properties, one part is transmitted and refracted and another part is reflected [2, 7].

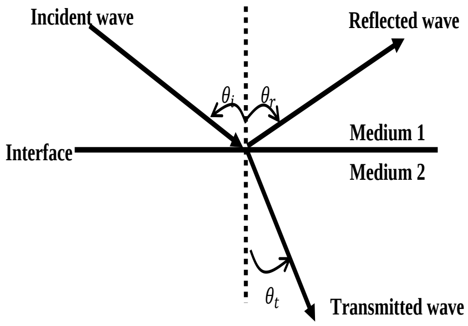


Fig. 4 – Diagram describing the change of propagation direction when the waves encounter changes material properties

The amplitude of the reflected radar energy is represented by the reflection coefficient, which is determined according to the permittivity contrast ratio. This coefficient is given by the following relation:

$$\rho_{1,2} = \frac{\sqrt{\varepsilon_{r_1}} - \sqrt{\varepsilon_{r_2}}}{\sqrt{\varepsilon_{r_1}} + \sqrt{\varepsilon_{r_2}}}, \tag{1}$$

where ε_{r1} and ε_{r2} are the dielectric constants of medium1 and medium2.

2.4 FDTD Method

The FDTD method is a method for solving Maxwell's equations in the time domain. FDTD is based on the Yee algorithm [8], which solves both the magnetic and electric fields in time and space. Since it does not use a wave equation, it does not study these two fields separately [5, 9, 10, 13].

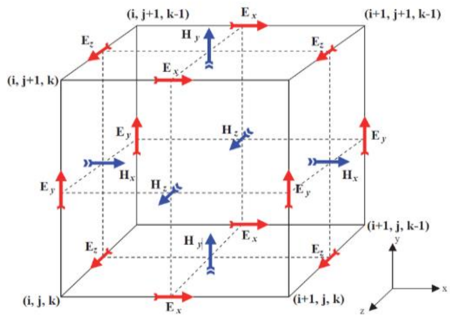


Fig. 5 – Yee cell (spatial discretization)

Maxwell's equations [2]:

$$\overrightarrow{\mathrm{Rot}}\left(\vec{E}(r,t)\right) = -\frac{\partial \vec{B}(r,t)}{\partial t} = -\mu\frac{\partial \vec{H}(r,t)}{\partial t}, \tag{2}$$

$$\mathrm{Div}\vec{D}(r,t) = \rho, \tag{3}$$

$$\mathrm{Div}\vec{B}(r,t) = 0, \tag{4}$$

$$\overrightarrow{\mathrm{Rot}}\left(\vec{H}(r,t)\right) = \vec{j} + \frac{\partial \vec{D}(r,t)}{\partial t} = \sigma\vec{E}(r,t) + \varepsilon\frac{\partial \vec{E}(r,t)}{\partial t}, \tag{5}$$

where $\vec{B}$ is the magnetic induction, $\vec{D}$ is the electric displacement, $\vec{H}$ is the magnetic field, $\vec{E}$ is the electric field, $\vec{J}$ is the electric current density and ρ is the electric load density.

For the TE mode, 2D FDTD equations become:

$$E_x\big|_{i,j,k}^{n+1} = \left(\frac{1-\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}}{1+\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}}\right) E_x\big|_{i,j,k}^{n} + \frac{\left(\frac{\Delta t}{\varepsilon_{i,j,k}}\right)}{\left(1+\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}\right)}\left(\frac{-H_y\big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}} + H_y\big|_{i,j,k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z}\right), \tag{6}$$

$$E_y\big|_{i,j,k}^{n+1} = \left(\frac{1-\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}}{1+\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}}\right) E_y\big|_{i,j,k}^{n} + \frac{\left(\frac{\Delta t}{\varepsilon_{i,j,k}}\right)}{\left(1+\frac{\sigma_{i,j,k}\cdot\Delta t}{2.\varepsilon_{i,j,k}}\right)}\left(\frac{-H_x\big|_{i,j,k+1/2}^{n+\frac{1}{2}} + H_x\big|_{i,j,k-1/2}^{n+\frac{1}{2}}}{\Delta z}\right). \tag{7}$$

3. MATERIAL AND METHOD

3.1 Material

Concrete can be considered a mixture of sand and large aggregates bonded together by cement paste. This cement paste, which consists of cement and water, may also contain chemical and natural additives. When we talk about concrete, we usually distinguish two basic components, aggregates and mortar. The latter consists of hydrated sand and cement, which contains various hydrated calcium silicates and aluminates.

Table 1 – Physical properties of materials

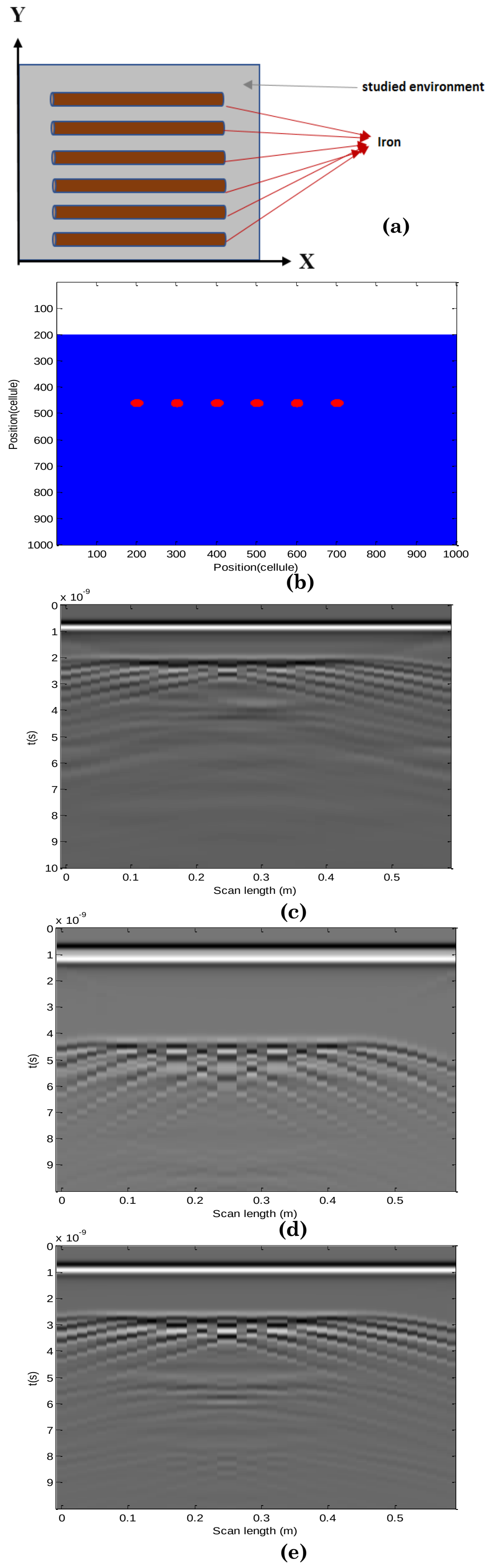
Material	Relative permittivity	Conductivity (S/m)	Permeability μ
Dry sand	3.0	0.0001	1.0
Wet sand	20	0.1	1.0
Dry concrete	6.0	0.005	1.0
Wet concrete	10.0	0.01	1.0
Iron	1.45	9000000.98	1.0

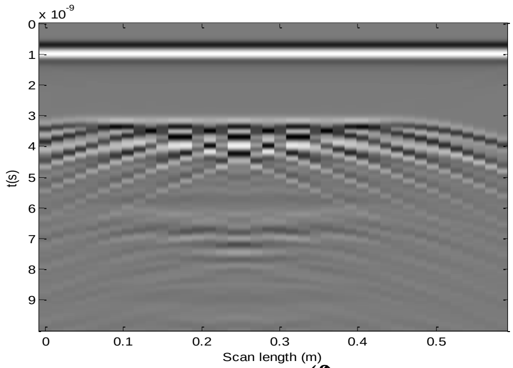
3.2 GprMax2D/3D

The program GprMax was developed in 1996 by Antonios Giannopolos [11] at the College of York in Iceland. It is an EM wave simulator that can be used for radar wave modeling. The GprMax suite consists of two programs: GprMax2D, a two-dimensional simulator, and GprMax3D, a full three-dimensional simulator, using the version best suited for the task at hand. In this work, only the 2D version of the program is used. It is based on the FDTD method applied to the time domain [6, 11].

4. RESULTS AND DISCUSSION

To simulate GPR signals of the proposed objects, the GprMax simulator requires a number of parameters such as the frequency of the antenna used, the geometry of the subsurface, and the dielectric permittivity, magnetic permeability, and electrical conductivity of the simulation media. There are common parameters for all profiles used. Throughout the simulation, the propagation mode is M-mode. The pulse used to simulate the incident wave is a Ricker pulse (derived from a Gaussian) with a frequency of 1.6 GHz and amplitude of 1 V/m.





(f)

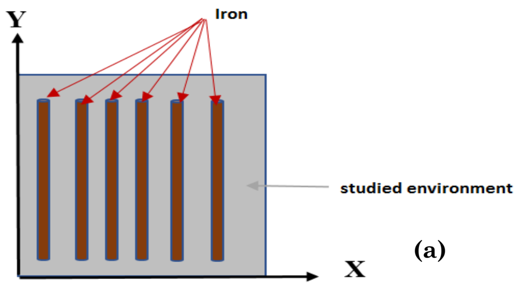
Fig. 6 – a) Profile 1 diagram, b) simulation of GprMax software signals for horizontally enclosed cylindrical iron bars, c) radargram obtained for dry sand, d) radargram obtained for wet sand, e) radargram obtained for dry concrete, f) radargram obtained for wet concrete

4.1 Profile 1

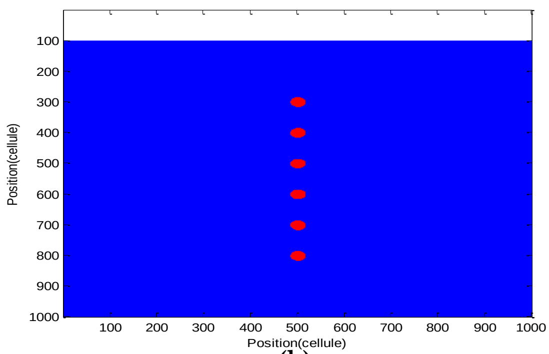
Profile 1 consists of six horizontal iron bars (in the shape of cylinders), as indicated in Fig. 6a. The examination areas are 0.5 m deep and 0.5 m wide.

Fig. 6b shows an example of the geometric model used to simulate the reflected radar signal from iron bars. The space this time is discretized as cells, with a spatial increment $\Delta x = \Delta y = \Delta l = \lambda/10 = 0.0005$ m. The total simulated size is set to 0.5 m × 0.5 m, which corresponds to 1000×1000 cells $((0.5/\Delta x) \times (0.5/\Delta y))$. The obtained results are summarized and presented by the software in the form of a radargram, as in Fig. 6c-f.

The presence of several hyperbolas can be seen on the figures. Remember that hyperbolas are an important element for detecting objects that indicate the presence of iron.



(a)



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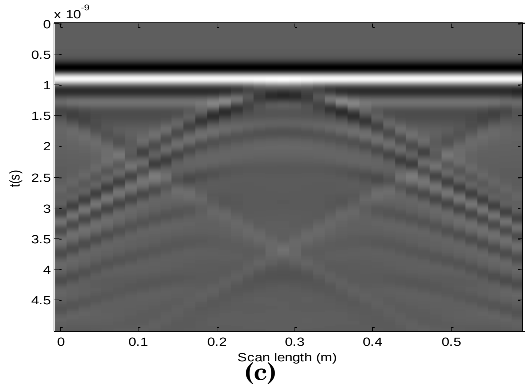

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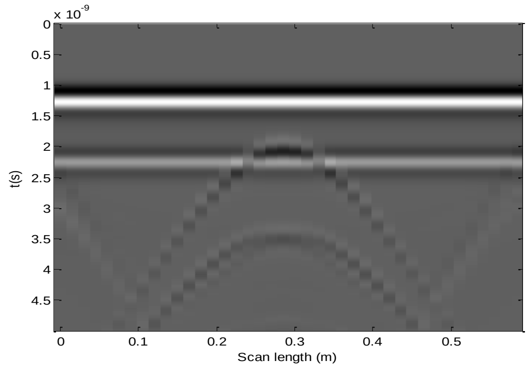

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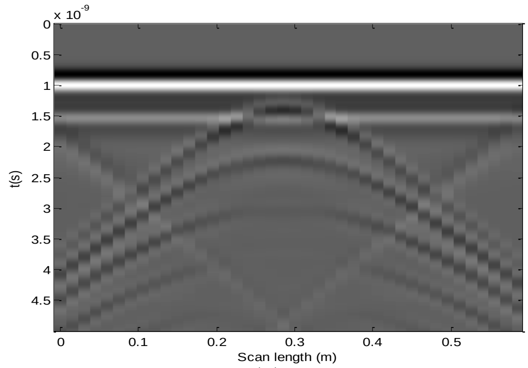

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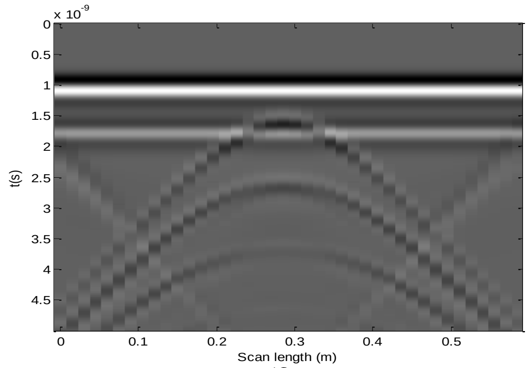


(f)

Fig. 7 – (a) Profile 2 diagram, b) simulation of GprMax software signals for vertically enclosed cylindrical iron bars, c) radargram obtained for dry sand, d) radargram obtained for wet sand, e) radargram obtained for dry concrete, f) radargram obtained for wet concrete

4.2 Profile 2

To illustrate the effect of electrical conductivity and permittivity on GPR signals, we took the same objects as in the previous case, but in the vertical direction and with the same medium as for Profile 1. The results of this study are shown in Fig. 7.

In this section, we modeled and simulated the detection of objects that are in vertical position. It is assumed that these objects are buried in a homogeneous medium. The simulation result is shown in Fig. 7. This B-scan shows the presence of hyperbolas of the objects that we assume are already buried.

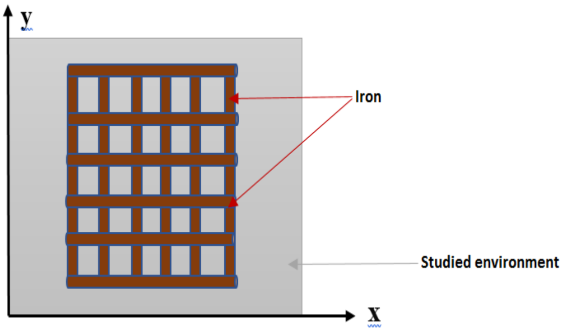
4.3 Profile 3

In this profile we have studied two media, the first one is the dry concrete and the second one is the wet concrete. We have modeled and simulated the detection of objects that are in vertical and horizontal positions. It is assumed that these objects are buried in dry and wet concrete. The simulation result is shown in Fig. 8.

This B-scan shows the presence of hyperbolas of the objects assumed to be already buried.

5. CONCLUSIONS

The goal of this work is to detect wetlands in concrete. To do this, the objects are first traced that has been buried in our environment. In our study, iron rods in sand and in concrete (dry and wet) are buried. The presence of hyperbolas in the obtained radargram shows the existence of buried objects in our environment. Thus, the first objective has been achieved. Comparing the radargrams obtained in the same profile and in the same medium (dry and wet concrete), the hyperbolas are noticed to be more evident and convex in the wet medium than in the dry medium. We also observe



(a)

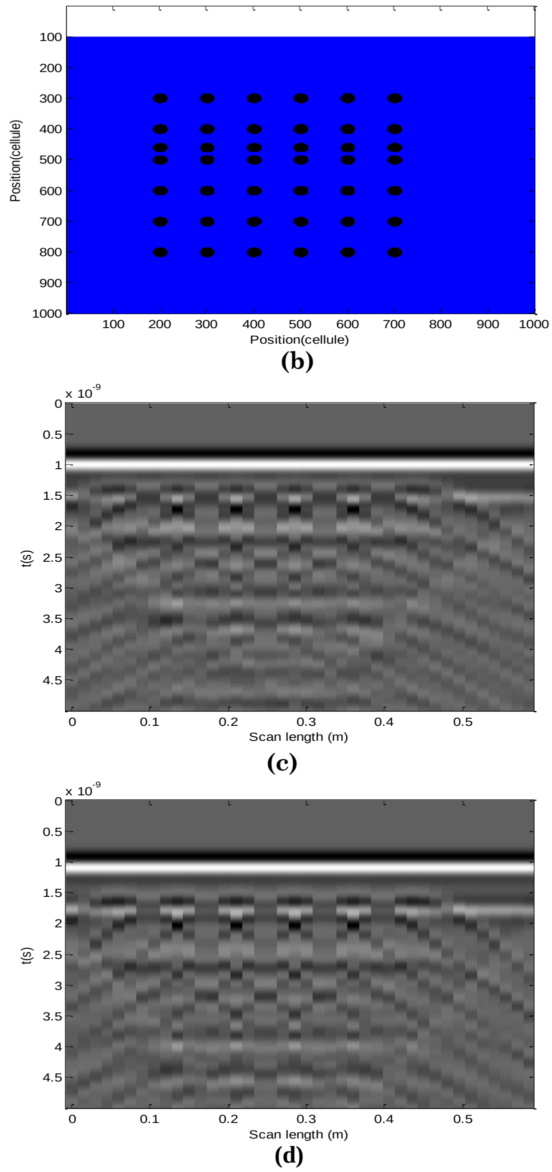


Fig. 8 – (a) Profile 3 diagram, (b) simulation of GprMax software signals for the iron bars of cylindrical shape, (c) radargram obtained for dry concrete, (d) radargram obtained for wet concrete

an increase in the amplitude of the reflected wave and a delay in the reception of the signal in the wet environment. Thus, the delay of the signal is due to the fact that the propagation speed in the wet concrete is lower than in the dry concrete.

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Оцінка стану заліза у вологих зонах за допомогою георадара з антеною-метеликом, яка працює на частоті 1,6 ГГц

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У роботі пропонується дослідження стану заліза у вологих зонах за допомогою георадара (GPR), що працює на частоті 1,6 ГГц. Останній є геофізичним інструментом розвідки, який аналізує поширення, заломлення та відбиття електромагнітних (ЕМ) хвиль високої частоти (від 300 МГц до 2,3 ГГц). Щоб відтворити GPR сигнали, ми використали програму GPRMAX, яка дозволила нам моделювати електричні та магнітні властивості ґрунту, а також сам GPR. Було створено кілька моделей для повторення різних геологічних ситуацій. Моделювання почалося з прямокутного блоку як вихідної моделі. Перша і друга моделі є основними профілями, які ілюструють поширення ЕМ хвиль. Третя модель використовується для дослідження поширення ЕМ хвиль (відбитих хвиль) у сухому та вологому бетоні, щоб продемонструвати вплив вологи на ЕМ хвилі. Для моделювання різних властивостей діелектричного середовища було побудовано набір моделей. Ми змоделювали кілька різних фізичних середовищ, використовуючи підхід кінцевої різниці в часовій області (FDTD), що є методом, на якому базується код наукового обчислення програми моделювання GPRMAX. Коли радіолокаційний сигнал поширюється в навколишньому середовищі, наявність гіпербол вказує на наявність похованих об'єктів.

Ключові слова: Георадар (GPR), Антена-метелик, GPRMAX, FDTD, Геофізика.