Research Paper

Simulation and Assessment of a Reinforced Concrete Slab Using the GPR Method

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ABSTRACT

This article presents a study on the simulation and assessment of reinforced concrete structures using the Ground Penetrating Radar (GPR) method, applied to the slab of the Engineering Sciences Department (UFR Sciences de l'Ingénieur) at the University of Thiès. An on-site experimental survey was carried out to acquire radar measurements over a 3×2.75 m grid consisting of 5 longitudinal and 5 transverse profiles. The measuring device used was a GSSI Radar with a 1600 MHz antenna, prospecting to a depth of 30 cm, with a sampling interval of 2 cm and a measurement window of 10 ns. The experimental study was coupled with a numerical simulation of electromagnetic wave propagation performed with the GPRMax computational code. The simulated model consisted of a reinforced concrete slab with four rebars spaced at 20 cm and a solid PVC pipe, along with a crack located at the top of two reinforcements. The experimental method provided radargrams that enabled the identification of the position and arrangement of the rebars as well as zones showing density variations or internal defects. This identification was enhanced by recognizing the radar signatures of objects crossed by the electromagnetic waves, as produced by GPRMax profiles. The compilation of radargrams according to the survey grid yielded a 3D imaging output highlighting the asymmetric arrangement of the reinforcement layers. The comparison between experimental and simulated results validated the reliability of the simulation and demonstrated the effectiveness of the GPR method for the non-destructive evaluation of reinforced concrete structures. This approach constitutes a valuable tool for preventive maintenance and for planning interventions on infrastructures.

Keywords: Simulation, assessment, GPR, GPRMax, UFR Sciences de l'Ingénieur

INTRODUCTION

Reinforced concrete remains one of the most widely used materials in civil engineering due to its versatility, mechanical strength, and durability [1]. The durability of reinforced concrete infrastructures is closely linked to their ability to withstand mechanical loads and environmental aggressions. However, internal defects such as cracks, voids, or reinforcement corrosion are not directly visible and remain difficult to detect using conventional inspection methods [2]. In this regard, Ground Penetrating Radar (GPR) is recognized as a promising non-destructive testing technique [3], [4]. The radar method relies on the propagation of electromagnetic waves through the material and on the analysis of signals reflected by interfaces between media of different permittivity. It thus enables the localization of reinforcements, the

identification of voids or cracks, the measurement of slab thickness, and the anticipation of potential structural risks [5], [6]. Nevertheless, its actual effectiveness depends on numerous factors: the electromagnetic properties of concrete, reinforcement depth, acquisition conditions, and the capacity to interpret signals [7]. In this respect, the use of numerical simulation in support of experimentation helps refine data interpretation, model different degradation scenarios, and optimize measurement parameters [8].

The present work falls within this perspective and proposes a study combining radar inspection and simulation applied to a reinforced concrete slab of the Engineering Sciences Department (UFR Sciences de l'Ingénieur). Within this framework, a central question arises: to what extent does the radar method, supported by numerical simulation, provide a reliable and accurate assessment of reinforced concrete structures, particularly in the case of the UFR Sciences de l'Ingénieur slab?

To address this question, the following objectives are set:

- Analyze the physical principles of electromagnetic wave propagation in reinforced concrete.
- Assess the capacity of the radar method to characterize the internal properties of structures (thickness, heterogeneities, reinforcement).
- Compare experimental results with simulation outputs to identify convergences and divergences.

To achieve these objectives, the following methodology will be adopted:

- Carry out a radar inspection campaign on the UFR Sciences de l'Ingénieur slab.
- Develop numerical models simulating wave propagation within the slab to test different scenarios (thickness variations, presence of defects, reinforcement density).
- Compare simulated and measured radar signals to enhance the interpretation of collected data.

MATERIALS & METHODS
The study includes an experimental phase and a numerical simulation phase

Experimental phase
In the experimental phase, the Ground Penetrating Radar (GPR) method was adopted for inspection

Presentation of the Radar Method
Ground Penetrating Radar (GPR), also known as subsurface radar, is a non-destructive geophysical method based on the propagation of high-frequency electromagnetic waves through a material (soil, concrete, pavement, etc.) [9]. Its main advantages include rapid data acquisition and large-area coverage, sensitivity to changes in density, moisture, and concrete composition, as well as its non-destructive nature compared to coring or drilling.

An emitting antenna transmits an electromagnetic pulse into the material. When the wave encounters an interface between two media with different electrical properties (permittivity, conductivity), part of the signal is reflected and recorded by the receiving antenna. The analysis of these reflections makes it possible to detect objects, interfaces, cracks, voids, or reinforcements (Figure 1).
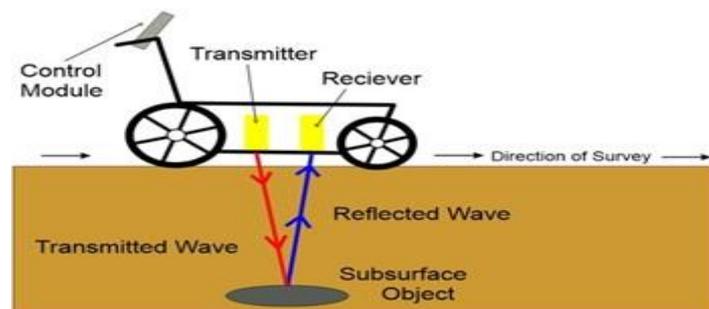

Figure 1 : Principal propagation of Radar wave [10]

The fundamental equation of radar wave propagation forms the basis of interpretation methods and is expressed as follows:

$$\nabla^2 E + k^2 E = 0 \quad (1)$$

Avec $k^2 = \omega^2 \mu \varepsilon - i\omega\mu\sigma \quad (2)$

$$\omega = 2\pi f \quad (3)$$

$\mu \sim 1$ for geological materials

σ : conductivity

ε : permittivity

Through Equation (2), it becomes clear that at high frequencies, permittivity is the dielectric parameter that is expressed. Consequently, in radar prospecting, permittivity is the parameter exploited.

The permittivity of a material is defined as the ratio of the magnitude of the electric displacement field to that of the applied electric field.

The average propagation velocity of radar waves in a geological medium is expressed as follows:

$$v = \frac{3 \, 10^8}{\sqrt{\varepsilon_r}} \quad (4)$$

where ε_r is relative permittivity $\varepsilon_r = \varepsilon / \varepsilon_0$.

The attenuation of radar waves in a medium is expressed as follows:

$$\alpha = 1.69 \frac{\sigma_e}{\sqrt{\varepsilon_r}} \quad (5)$$

The attenuation is expressed in dB/m

The velocity and attenuation of radar waves therefore depend on permittivity and conductivity. By measuring the travel time and the amplitude of the signal transmitted from a source to a receiver, it is possible to deduce the characteristics of the medium traversed. The particularity of concrete, as a mixture of different constituents, gives it a highly variable permittivity depending on the volumetric fractions of its components [11]. However, the permittivity values generally reported by most authors after various studies range from about 4 to 12.5. For dry concrete, a value of 5.5 can be considered as a reference input [12].

In the past, radar-based inspection has proven effective through the results of several studies. Liu et al. (2007) demonstrated that radar can determine the depth and spacing of steel bars with good accuracy, even under field conditions. Gucunski et al. (2013) applied GPR to assess the condition of concrete bridge decks, identifying delaminated and deteriorated areas. Tešić, Baričević, and Serdar (2021) provided a detailed review of radar detection methods applied to corrosion, highlighting both current advances and limitations. Tosti & Ferrante (2020) showed that radar is effective for the non-destructive measurement of slab and pavement layer thickness.

Despite its potential, several factors reduce the reliability of GPR:

- Signal attenuation in highly conductive or water-saturated concrete;
- Difficulty in distinguishing multiple signals (reflections from reinforcement, defects, interfaces);
- Dependence on experimental conditions (antenna frequency, depth, geometry).

These limitations highlight the need to combine GPR with other approaches, such as numerical simulation (gprMax, FDTD), which allow a better understanding of wave–material interactions and improve interpretation [13].

Presentation of the Acquisition and Processing Setup

The acquisition setup (Figure 2) consists of:

- Central unit (control console / integrated computer): Acts as the "brain" of the system, including the command interface and a data storage system.
- Radar antenna: The key component responsible for transmitting and receiving electromagnetic waves. Antennas are available in different frequency ranges, but the SIR 3000 antenna operates at high frequency (1600 MHz), providing high resolution (millimetric details) with limited penetration (a few tens of centimeters up to about 2 m). Antennas can be:
- Shielded: Used in urban environments or on concrete, as it minimizes lateral interferences.

o Unshielded: Used for open-field surveys, such as in geology or archaeology.
• Mobile cart or support system: Allows the antenna to be moved smoothly and regularly over the surface under investigation. It may be equipped with:

o Position sensors (odometer / GPS): For georeferencing measurements.
o Calibrated wheels: Ensuring regular data acquisition at precise intervals.
• Power supply system: Rechargeable batteries (typically lithium-ion), providing several hours of autonomy.

Figure 2 : Presentation of Radar setup [14]

Data processing is performed using Radan 7 [15], a software for data processing and visualization that enables the conversion of raw signals into radargrams (2D cross-sections of the subsurface) or 3D models. The software includes functions for filtering noise, depth correction based on the wave propagation velocity in the material, and hyperbola interpretation, which correspond to the typical signatures of discrete objects such as cables or reinforcing bars.

Numerical simulation phase
The study of physical phenomena has significantly advanced in recent years with the emergence of numerical simulation tools. These tools enable the creation of models and the virtual investigation of the phenomena occurring within them, yielding results that closely approximate reality [16]. In the context of this article, GprMax will be used

to better understand the phenomena that occur during ground-penetrating radar (GPR) surveys. GprMax is an open-source software available online. It is written in Python and allows the simulation of electromagnetic wave propagation, such as those used by radar systems. Its computational method is based on the finite-difference solution of the discretized Maxwell's equations [17]. The program implements the Yee algorithm, which simultaneously solves the electric and magnetic field equations in both time and 3D space.

RESULT
The radargrams represent the amplitude of the reflected wave as a function of the distance travelled along the profile (horizontal axis) and the transit time (in ns). Radargrams (B-scan) are obtained by

superimposing the 150 amplitude curves corresponding to each sampling step called trace or A-scan.

The data collected and recorded in the control unit by the ground-penetrating radar are formatted and processed using the Radan7 software, which provides a visual of the profile. This data is the result of a standard imaging treatment of the characteristics of the electromagnetic waves emitted and reflected by the profile in accordance with the images presented on the control unit. The profiles obtained after treatment are represented in figure 8.
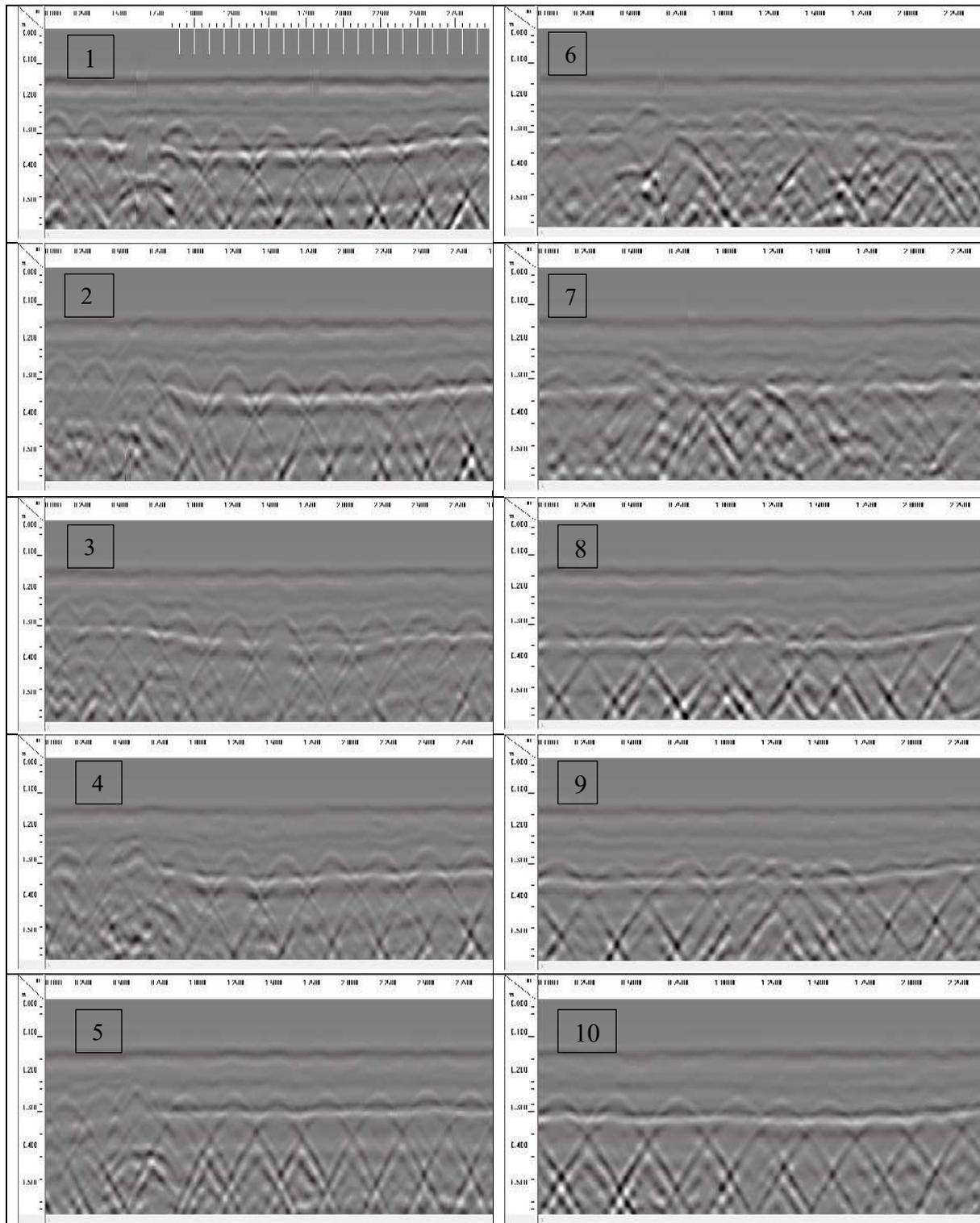
Figure 3 : Profils radar bruts mesurés

The characteristic events noted are the appearance:

• Of the direct wave at the top of the radargram corresponding to the quasi-horizontal dark light band.
• Typical diffraction hyperbolis of rebar.
• Ringing (reverberations): parallel repetitions of a strong echo.
• Plane interfaces: sub-horizontal bands materializing the background of the auscultated structure.

In order to facilitate the interpretation and identification of objects encountered in connection with physical principles, the results of GPRMax simulation will be exploited.

Results of GPRMax simulation

After simulation on GPRMax, the model created by compiling 365 traces and improved under Photoshop is presented in Figure
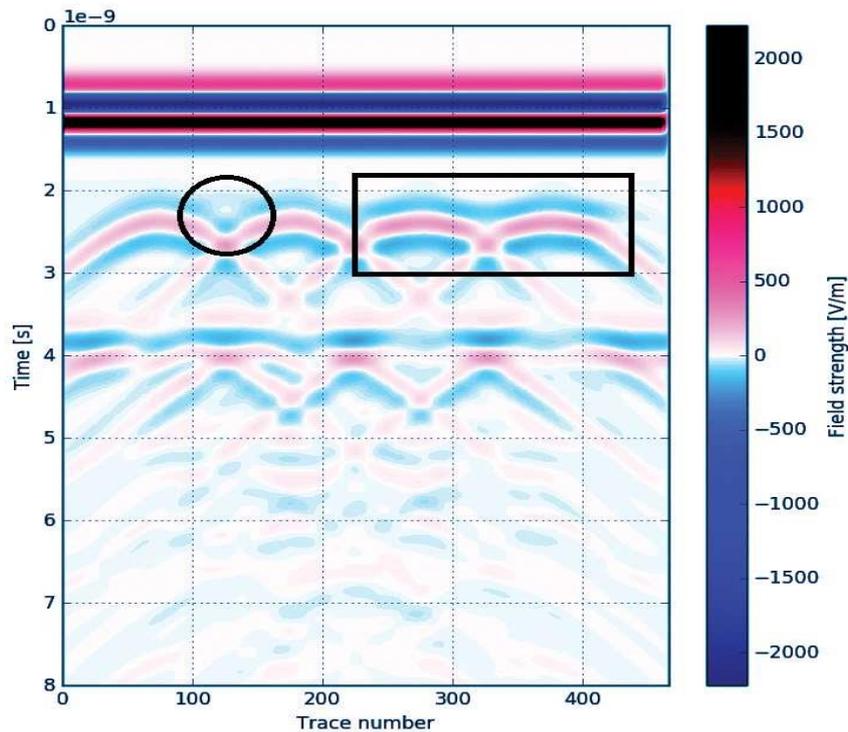

Figure 4 : Profil obtenu par simulation GPRMax

The first two bands (pink and blue) correspond to the surface echo and the black band corresponds to the air-concrete interface. The diffraction hyperbolis represent the reflections of waves on cylindrical steel frames. The presence of the PVC tube, on the other hand, is less pronounced than that of the reinforcements explained by the small difference in permittivity; but a slight blue curve appears in the encircled area which corresponds to the reflection of the wave on the surface of the PVC tube. The presence of the crack above the last two reinforcements tends to flatten the two hyperboles compared to the

first two. These slightly flattened hyperbolas are represented in the rectangular area. The concrete-air interface at the bottom of the slab corresponds to the blue color line just above the time at 4 ns.

This simulation allows to see the air-concrete boundaries and to highlight the Radar signature of encountered objects in order to facilitate their detection in the measured radargrams.

Results of prospecting on the slab

Based on the signatures obtained at the end of the simulation, it becomes easy to analyze and interpret profile 1 (Figure 10) as follows:
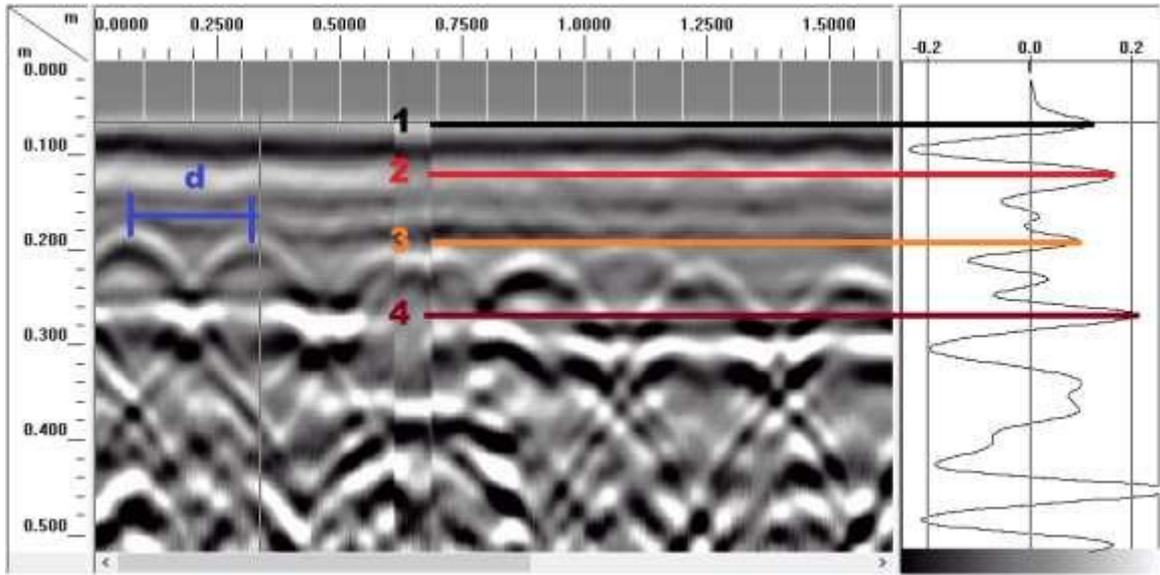
Figure 5 : Interpreted Profil 1

There appear at the level of this profile four interfaces corresponding to levels of positive amplitudes represented by the color of white shade and which can be interpreted as follows:

- 1: Air-concrete interface1: corresponding to the upper level of the slab precisely the surface of the tile;
- 2: Mixer interface1-mixer 2: corresponds to the lower limit of the mixer 1 (concrete with a slope shape + tiles) and the beginning of the mixer 2 corresponding to the concrete of the load-bearing slab containing the reinforcements;

- 3: Interface concrete2-reinforcement: corresponds to the roof of the reinforcing steels of the slab;
- 4: Béton2-air interface: corresponds to the lower finished surface of the slab in contact with the air in the rooms;
- d: distance between the tip of two hyperbolas that corresponds to the spacing between the reinforcements of the slab. Profile 1 after treatment with the structurescan module presents a clearer imaging (Figure 11).
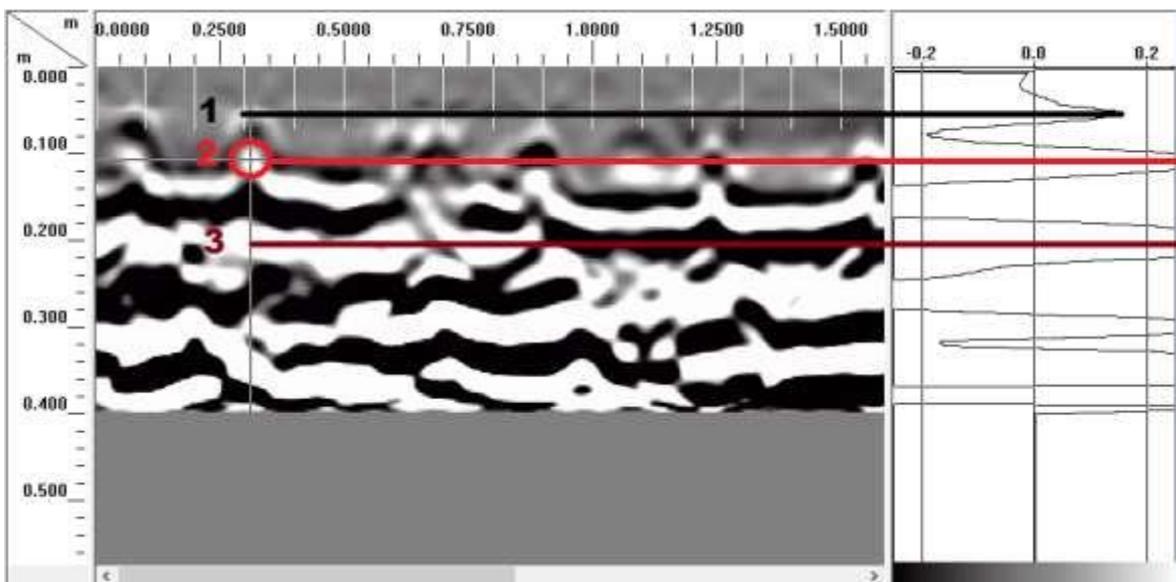

Figure 6 : Profil 1 treated using structure scan module

The advantage of the treatment with the structurescan module is that it allows for a migration that brings back the hyperboles created by the reflection of the wave on the steel into points that represent the encountered steels. The number 2 on the diagram illustrates a hyperbola converted to a point. The interface béton1-béton2 is identified by the number 1 and the interface béton2-air by the number 3. Furthermore, on this module an automatic correction applies and matches the level of the first amplitude (air-béton1 interface) to the zero depth level. This module allows other more advanced functions such as spotting and identifying targets.

Ultimately, we can therefore visually define the following geometric elements:

- Concrete 1 about 6cm
- Concrete 2 about 14cm
- Spacing of the frames approximately 30cm
- The coating of the frames about 6cm

The accuracy being in the order of centimeters, it is difficult to accurately define the thickness of rebar which are very small. We also notice the geometric imperfections in the thicknesses of the layers resulting from the execution. The spacings of the reinforcements are not constant and can vary up to 5cm. We note a flexure of the slab starting from 90 cm in profile 112 and this flexure can be estimated at 2 cm compared to the previous section. The determination of the real permittivity of the material was done on the thickness of the concrete 2 $\varepsilon_r = \left(\frac{c \times t}{2h}\right)^2$

$$(6)$$

$$\varepsilon_r = \left(\frac{3.10^8 \times 2.27.10^{-9}}{2 \times 0.14}\right)^2 = 2.95$$

Then the new thickness calculated with this permittivity value is presented as follows: $h = \left(\frac{c \times t}{2\sqrt{\varepsilon_r}}\right)^2$ $\quad (7)$

$$h = \left(\frac{3.10^8 \times 2.27.10^{-9}}{2 \times \sqrt{2.95}}\right)^2 = 0.145 \text{ m}$$

The permittivity value (5.5) entered for the data acquisition, which is slightly different from the actual value (5.91), has very little influence on the thicknesses obtained. The thickness values obtained on the radargram are therefore preserved.

A section of the 3D model provides an overview of the arrangement of the reinforcement in the studied area (Figure 12).
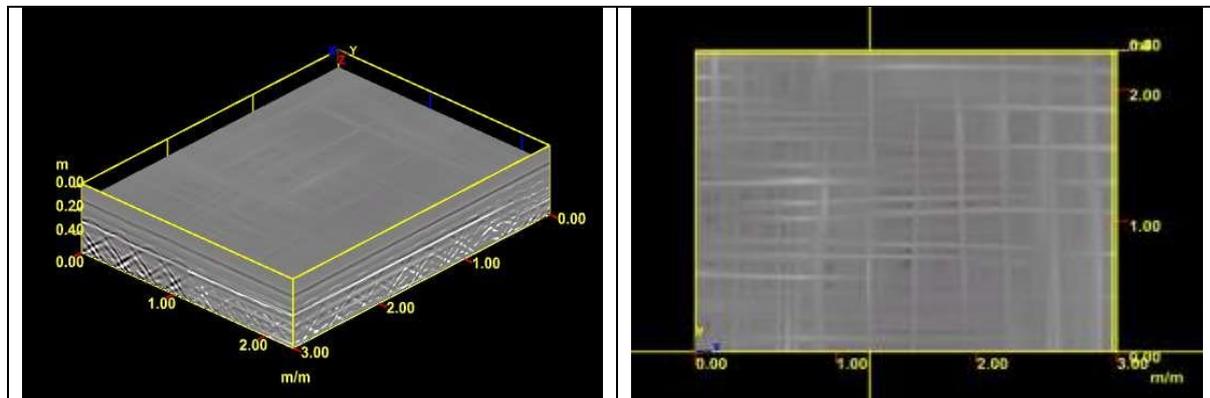

Figure 7 : Modèle 3D mettant en évidence la disposition du ferraillage

CONCLUSION

In conclusion, this study demonstrates that the combination of auscultation by radar method and numerical simulation constitutes a robust and reliable approach for the non-destructive evaluation of reinforced concrete structures. The experiment carried out on the slab of UFR SI, using the GSSI 1600 MHz radar, made it possible to acquire detailed data over a depth of 30 cm, with a fine spatial resolution. The analysis of radargrams revealed the current position and arrangement of the reinforcements, as well as areas with density variations and internal defects. The compilation of measurements on a regular grid allowed the generation of 3D imagery, highlighting the dissymmetrical arrangement of reinforcement beds and

illustrating the outdated state of the studied slab.

The numerical simulation carried out under GPRMax, faithfully reproducing the experimental conditions, including cracks and inclusions, allowed to model the propagation of electromagnetic waves in the structure. The comparison between the experimental results and the simulated results showed a significant agreement, validating the reliability of the model and confirming the ability of the radar method to accurately detect internal elements and structural anomalies.

These results highlight the interest of the radar method as a preventive maintenance tool, allowing to anticipate the evolution of structures, optimize interventions and reduce costs associated with premature deterioration. However, certain limitations must be taken into account, notably the complexity of interpretations in highly heterogeneous structures, and the need for precise calibration of simulation parameters for each type of structure.

For the future, this study opens interesting perspectives. The integration of advanced signal processing and artificial intelligence techniques could improve the automatic interpretation of radargrams. Moreover, the extension of this methodology to more complex structures, larger dimensions or in composite materials, would allow to widen its scope in the field of civil engineering. Finally, the combination with other non-destructive auscultation methods, such as ultrasound or thermography, could offer a more complete and reliable assessment of the state of the infrastructures

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