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Characterization of the Radar Waves Gpr by Digital Simulation for the Auscultation in Civil Engineering

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Abstract- The numerical simulation of non-destructive testing of the materials has made considerable progress in the recent years. This simulation allows not only to increase the efficiency and the potential of the non-destructive testing methods, but also to expect the results of a particular technology and to define the most efficient conditions of achievement, while reducing the costs of progress. The purpose of this presentation is to show the important contribution of the computer simulation as regards the auscultation of the reinforced concrete slabs by GPR technique. The cases of the water infiltration and the chloride ions as well as the delaminations are considered.

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I. Introduction

Among the current pathologies that affect the reinforced concrete structures is the increase of the corrosion. This corrosion is caused by the infiltration of water and chloride ions. The GPR technique is very practical in recent years to assess the probability of the increase of the corrosion in reinforced concrete elements according to two approaches. The first approach considers the attenuation of the waves reflection on the armatures or structures of the controlled parement and the second approach considers the waves reflection on the basis of the controlled reinforced concrete element. Furthermore, the detection of the delamination at the level of the upper structures is also performed according the two approaches mentioned above. The analysis of the records elements is based on the fact that the places where we record low reflections are the places where the possibility of corrosion is strong as well as the delamination. This article aims to choose the most reliable approach and this by means of the numerical simulation.

II. Pathology of Concrete Structures

a) Cracking

It is important, first of all, to emphasize that it is impossible today to avoid the cracking of the concrete, either during the implementation that is due, for example, to the drying shrinkage or on hardened concrete due the material aging. Thereafter, the corroded armatures which have a larger volume than the steel in good condition, the concrete pressure state in the place of a corroded reinforcement is more important and the cracking breaks. [1]

b) Concrete carbonation

The carbonation is a cause of corrosion of reinforced concrete structures and destabilizes their hardiness. It is a natural phenomenon of dissolution of the carbon dioxide from the air in the interstitial solution of the concrete, followed by acid-basis reaction with the basic compounds such as the portlandite, to form calcium carbonate. This results in a decrease in pH and reinforcement corrosion.

The relative humidity of the surrounding environment is a fundamental parameter. Indeed, in order that the process continues, we need a supply of humid carbon dioxide. However, the diffusion of the dioxide takes place 10,000 times faster in the air than in water. The relative humidity must be low enough that the release of carbon dioxide is possible, but it must also be sufficiently important for the occurrence of the carbonation reaction itself. [5]

The concrete carbonation is a slow phenomenon. Its speed depends on many factors such as the compactness, the percentage in the cement, the type of cement, the water content in the concrete, the degree of hydration of cement, the carbon dioxide concentration of the air, the relative humidity of the air, the temperature. More the carbon dioxide content of the air is higher; more the speed of carbonation is fast.

The influence of the compact is shown in Picture 1. The carbonation speed decreases when the quantity of water in the concrete decreases. Indeed, a reduction of the mixing water reduction reduces the porosity of the concrete, which slows the penetration of the carbon dioxide. The carbonation speed decreases also when the cement content increases [2].

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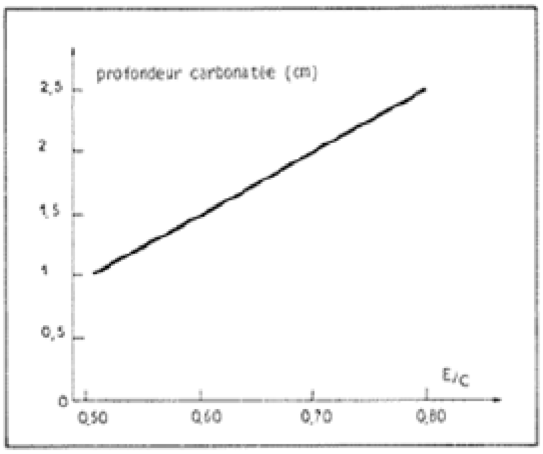


Picture 1: Influence of E / C rate on the carbonate depth after three years.

The reactions that may occur in ambient conditions are:

- Dissolution of iron using the anode:

$$Fe \longrightarrow Fe^{2+} + 2e^- \qquad \text{(Eq. 1)}$$

- corrosion of water using the cathode:

$$H_2O + 1/2\ O_2 + 2e^- \longrightarrow 2\,OH^- \qquad \text{(Eq. 2)}$$

- Migration OH- ions using the anode:

$$Fe^{2+} + 2\,OH^- \longrightarrow Fe(OH)_2 \qquad \text{(Eq. 3)}$$

A schematic representation of these reactions is noticed in Figure 2.

In the presence of oxygen excess, Fe (OH)2 is changed into Fe2O3 and FeO. According to the conditions, the composition of the oxidation products is variable and can be represented by the formula: (FeO) x (Fe2O3) (H2O)z [3].

d) Causes of the corrosion

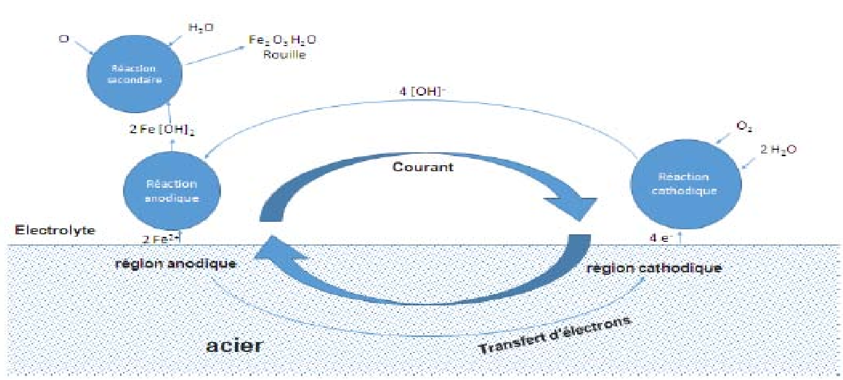
There are two main factors that contribute in the appearance of the corrosion in the reinforced concrete.

c) Reinforcement corrosion

When a metal is immersed in an electrolyte solution, the metal ions go into the solution, giving a negative charge to the metal. Two dissimilar metals immersed in the same solution will have a different potential and when connecting the two metals through a conductor, the electrons will move the metal which has the most negative potential (the anode) to the metal which has the least negative potential (cathode). So, we will achieve an electrolytic cell. A potential difference may also appear if one metal is used for two electrodes positioned in diverse electrolytes; this is called a concentration cell.

In the case of the steel of the armature, the electrolyte is in the porous structure of concrete and its composition may vary along the armature, resulting in the appearance of cells between the points at diverse potentials.

Firstly, there is the concrete carbonation. When the pH of the concrete drops below 9; the armatures are no longer passivated. This phenomenon is caused by the reaction between the hydrate of the cement paste and the atmospheric CO2. The other cause consists in the depassivation that occurs when the chloride content on the level of the armature exceeds a threshold. It is recognized that this threshold corresponds to a content of 0.4% compared to the mass of cement. [4]



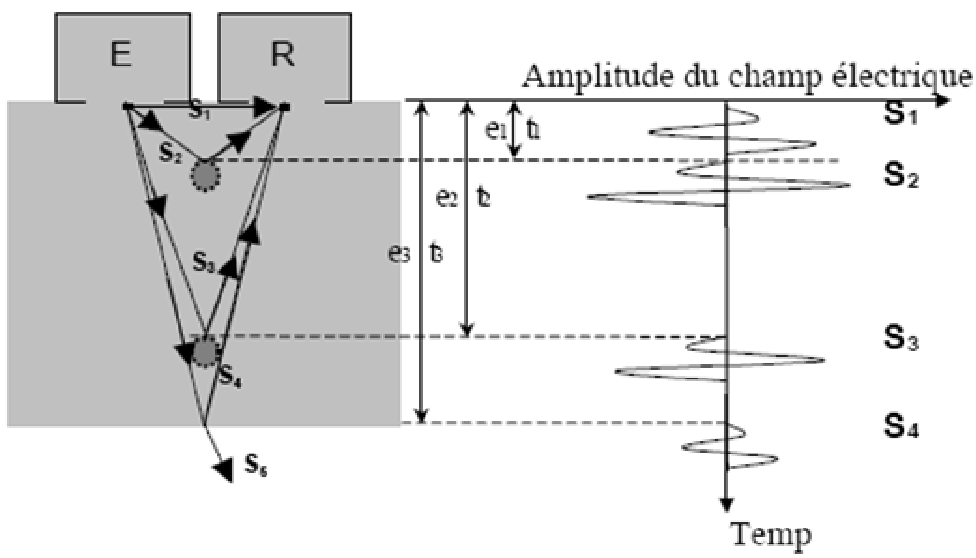
Picture 2 : Schematic representation of the electrolytic corrosion reaction.

III. General Principle of Technology Radar gpr and the Notions about the Electromagnetic Properties of a Environnement with Losses

Many authors reported the principle of radar auscultation in civil engineering

[9]; here, it is only about a fast description of the simplified principle of the structures auscultations of reinforced concrete by pulse radar coupled with antennas. This is a radar brand GSSI, model SIR 2000, using coupled antennas with central frequency about 1.5 GHz (GSSI 5100). A radar permits to send an electromagnetic pulse that will propagate by attenuating more or less in the auscultated environment. The Interfaces present contrast of electromagnetic properties reflects some of the energy emitted by the source. These manifestations are recorded by the receiver during a time interval predetermined by the operator and constitute a radar gram showing the signal amplitude received according the time. Picture 3 shows the type of radar gram that can be suggested to obtain a reinforced concrete slab with two beds of radar reinforcements according a bistatic mode by coupled antennas. In this example, the energy radiated by the antenna which is the "source signal" or "incident signal" is spreading in all directions of the half-space embodied by the air / concrete below the transmitter antenna (E).

A part of the incident signal is transmitted directly to the receiving antenna (R), the signal S1 which is the direct wave transceiver. Part of the radiated energy will be reflected on the armatures of the 1st and 2nd bed, which constitutes the signals S2 and S3 and so on for the following interfaces. Generally the antenna is moved over a linear profile and the radar grams are recorded following a centimetric step. These Radar grams are then processed by thresholding and are shown in grayscale or color. Their juxtaposition allows obtaining a two-dimensional image of the auscultated armature called "cut time", conventionally used for labeling the armatures.



Picture 3 : Schematic diagram of the radar auscultation on a reinforced concrete slab

The response of a non-magnetic material such as the concrete to an electromagnetic excitation is based on two parameters, the electric conductivity; s [S / m] associated with conduction currents and the dielectric permittivity, e [F / m] relative to the polarization phenomena. The concrete is not a perfect dielectric but a material of lost, its permittivity becomes a complex quantity that the imaginary part resulting losses. In addition, as the conductivity of the concrete is not zero, applying a variable electric field generates thus conduction current and a displacement current. The dielectric loss mentioned above, are therefore added ohmic losses by Joule effect. It is impossible, in the frequency range studied by radar technique (300MHz-2GHz), to distinguish the respective contributions of conduction and polarization phenomena.

We then define a relative effective permittivity (er) which is a complex combination of the permittivity and conductivity and allows to treat the material as a dielectric with a complex effective permittivity, the conductivity of the material being then taken into

$$\varepsilon_r = \frac{1}{\varepsilon_0}\left(\varepsilon + \frac{\sigma}{i\omega}\right) = \varepsilon_r' - i\varepsilon_r''$$

account by the imaginary permittivity part (Equation 4).

With ε_0 the dielectric permittivity of the void e0= 8.854.10-12 [F / m]

Where ε_r' and ε_r'' are the real and imaginary parts of ε_r and are respectively called dielectric constant and loss factor.

IV. Experimental Site

Within the structure and Rehabilitation Laboratory was realized a research program to evaluate the effectiveness of the radar technique to control the quality of concrete of reinforced concrete.

For this purpose several samples of concrete dosed at 350 kg / m3 with different depths of water infiltration and chloride ions were made and conserved in the laboratory,

Piture 4 : Auscultation of reinforced concrete panels by GPR technology

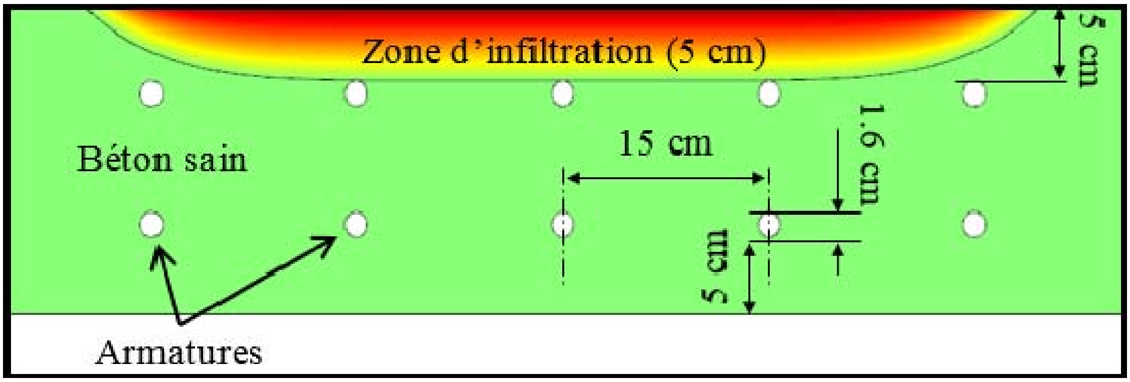
V. Simulation of Electromagnetic Waves Propagation in Concrete

If we assume that the electromagnetic waves propagation in the concrete can be likened to the propagation of a progressive monochromatic plane wave propagating in a specified direction, we show that the dielectric constant affects only the speed of propagation and that the attenuation is primarily due to loss factor. One goal of the development of a simulation tool is to verify these strong assumptions. For this, we suggested a numerical model of the radar antenna used, based on the finite difference temporal domain (FDTD) [6-8]. Through adequate modelized auscultating material, the simulation code allowed us to better understand the radiation of the antenna during its coupling with different materials and verify the two previous hypotheses on all the analyzed signals (direct or reflected). This code has also enabled to better analyze the propagation mode of the direct signal and show that it is divided into two signals; a first is propagating in air and a second propagating in the material. Finally we were able to highlight the impact of the dielectric constant of the coupling material in the shape of the radiation pattern.

VI. Application to the Infiltration of Water and Chloride ion in Concrete Slabs

a) Simulation models

This work intends to study the effect of water and chloride ions infiltration in a reinforced concrete slab on the propagation of GPR waves. For this, we proceed to the simulation of reinforced concrete models infiltrated with solution at different depths from the surface. The model represents a reinforced concrete slab 30 cm thick. Two rows of armatures are also introduced to the interior of the slab. The geometry of the model is shown in Picture 5 below.



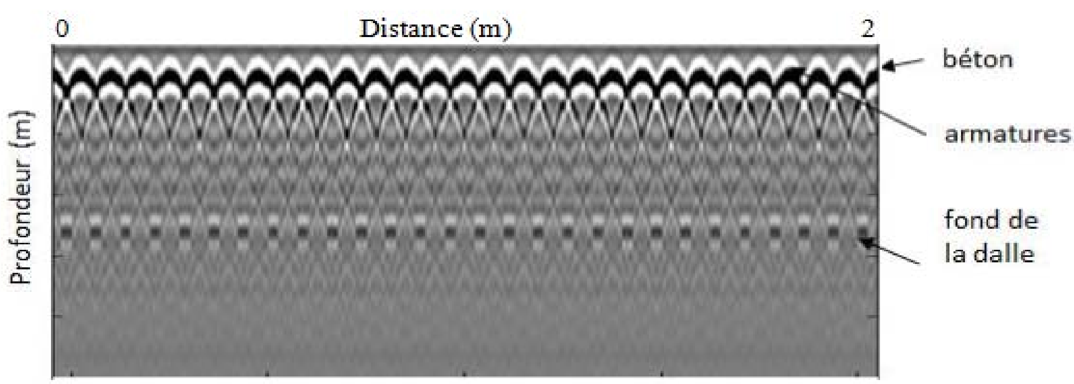
Picture 5 : Illustration of model infiltration to 5 cm deep

For this work, five different models are simulated corresponding to depths of infiltration of 2.5 cm, 5 cm, 10 cm, 15 cm and 20 cm from the surface, in addition to a referential model representing a slab without infiltration .

The infiltration area is characterized by a high permittivity by ensuring the transition with sound concrete and this on a thickness of 5 cm when there is saturation [6]. The permittivity ε and the conductivity of the concrete in normal and saturated state are deduced from the literature [7,8]. We imposed, for a frequency of 2 GHz, worth $\varepsilon^* = \sigma = 11$ and 400 mS/m at saturation and $\varepsilon^* = 5$ and $\sigma = 100$ mS/m for a sound concrete [7] The geometry of the infiltrated volume is designed as respecting the condition of penetration equal depth to the source surface. This penetration provides a transition to the healthy properties of concrete and extends over a maximum thickness of 5 cm when there is saturation at the surface. In this case, when the total depth of penetration is greater than the maximum thickness transition (5 cm), a saturation volume appears on a further depth.

b) Simulation results

The picture 6 shows the radar gram corresponding to the referential model (hardened concrete). We distinguished the reflection at the concrete surface, superior armature and reflection on the bottom of the slab. Reflections on the lower plates are not visible because they are hidden here by the upper frames.



Picture 6 : radar gram corresponding to the reference model

The reflections presented below appear clearly affected by the infiltration of the water and the chloride ions in the concrete, especially from 5 cm deep. Indeed, as the infiltration area is characterized by higher permittivity and conductivity, it transmits more delayed and attenuated reflections. This is found either on the reflections on the 5 central armatures covered by the infiltrated area on reflections or on the reflections the base of the flagstone.

This effect on the reflections affects only the echoes of the targets located in the infiltration. This clearly appears on the radar grams for different depths where there is the echo from the base of the slab is more weakened when the infiltration is deeper, whereas the echo armature remains unaffected from 10 cm depth. These results specify that the reflection of GPR waves on the flagstone base is more sensitive to the infiltration of water and chloride ions in the slabs. This can be explained by the fact that the wave is affected by the properties of the concrete with a thickness about 30 cm compared to a concrete cover of 5 cm of thickness.

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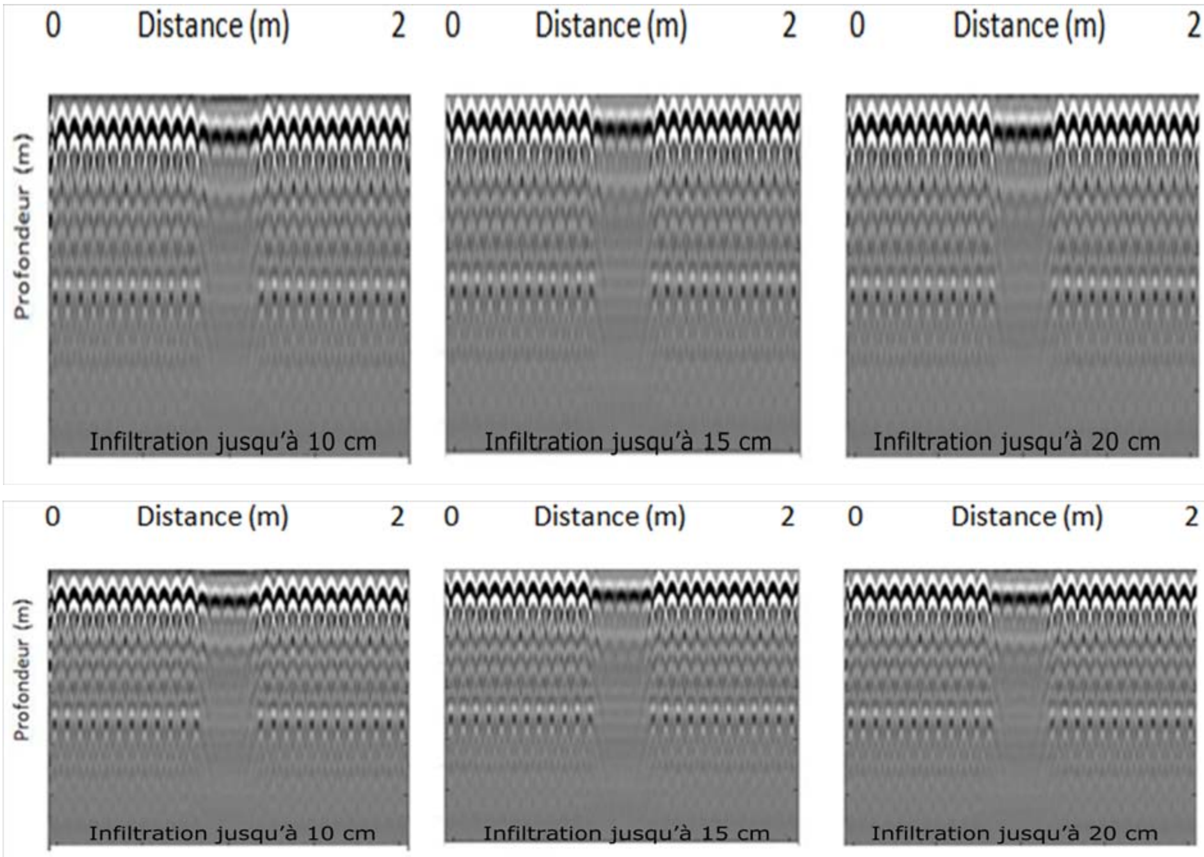
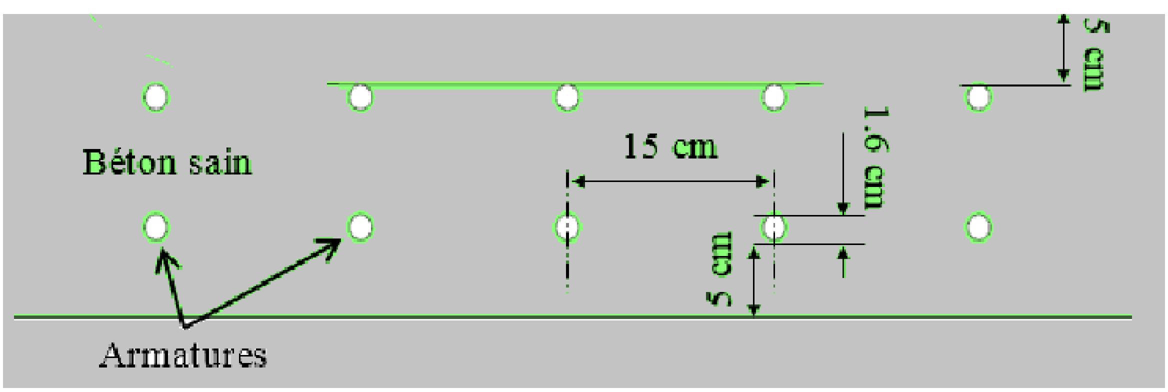


Picture 7 : Results of numerical simulations of the infiltration

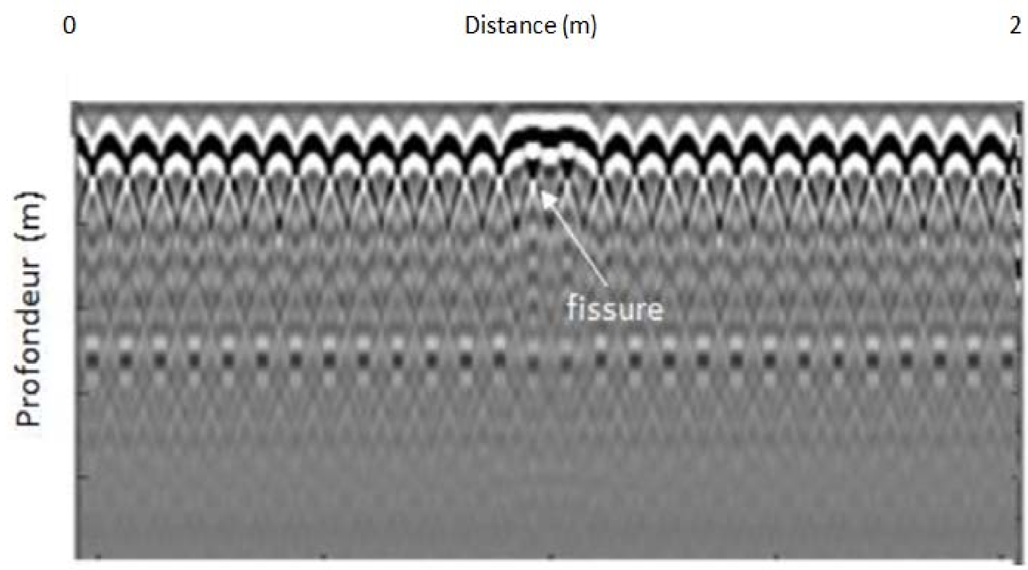
VII. Simulation of a Delamination

The delamination in the concrete is one of the most frequently encountered anomalies that appear mostly in the upper armatures. In order to predict its detectability, a fissure is introduced into a model of sound reinforced concrete (without infiltration of water nor chloride ions). The fissure has an aperture of 0.5 mm, a length of 300 mm and contains water with a salinity of 15 ppm, which is reflected in the model by a complex permittivity medium.



Picture 8 : Model of fissure in reinforced concrete

The radar gram related to this model of delamination (Picture 9) reveals a clear reflection corresponding to the fissure between the three central armatures. The fissure effect results in a significant distortion of the image of the armature. These armatures appear indeed as defined hyperbole when they are in a healthy non-delaminated concrete. Moreover, this reflection does not mask echoes from lower targets (bottom of the slab). In other words, the presence of this delamination is not a great effect on the intensity of the reflection on the bottom of the slab. As a result, in this case, the analysis of the waves reflection on the armatures and informative on delamination of the concrete in the upper armatures than the analysis of more reflection on the bottom of the tiles.



Picture 9 : Result of simulation at 2 GHz in a reinforced concrete

VIII. Conclusions

The Numerical simulations of the propagation of GPR waves in this article indicate that they allow to clearly detecting the deterioration of concrete by water and chloride ions leakage and by the delamination. It has been also demonstrated by the simulations that the reflection of GPR waves on the bottom flagstone is more sensitive to the infiltration of water and chloride ions in the concrete than the reflection on the armatures. Similarly, it has been proved that the detection of the delaminating of the concrete at the top row is easier whereas the wave reflection at the upper armatures rather than the reflection on the bottom of the slab.

The numerical simulation of the wave's propagation phenomena in building materials is therefore useful for the prediction of the test results to optimize the test conditions, to help in the interpretation of statements and for the development of new testing procedures.

IX. Acknowledgement

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