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Simulation study on the influence of a dielectric constant gradient in the concrete on the direct wave of GPR measurements

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ABSTRACT

Ground Penetrating Radar (GPR) is a non-destructive technique based on the propagation of electromagnetic wave, the propagation characteristics (speed, level of signal attenuation, ...) depend on the electromagnetic properties of the material through which it passes, where the dielectric constant of the material is one of the key parameters. Previous studies mainly based on the analysis of reflected signals to evaluate the transmission medium. Recently, the research to exploit the application of GPR direct wave (wave propagate directly in the material from the transmitting antenna to the receiving antenna) for characterization of the structural materials is becoming a matter of great interest.This paper focuses on studying on the influence of a gradient of dielectric constant in concrete on GPR direct wave, and at the same time evaluates the survey depth of GPR direct wave in concrete materials. The studying was carried out by simulation method based on GPRmax - 2D software fortwo concrete models with two gradients of dielectric constant and simultaneously with two antennas with center frequencies of 1.5 GHz and 2.6 GHz, respectively.Analysis of the obtained simulation results allows to evaluate the influence of the dielectric constant gradient on the GPR direct wave and the survey depth of the GPR direct wave.

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1 Introduction

GPR is a non-destructive technique, widely and effectively applied in many different construction fields [1, 2] such as:

- Detect reinforcement, prestressed cable ducts, voids, cracks and stratification, etc.
- Measure the thickness of structural layers of pavement and concrete slabs; measuring the depth of reinforcement mesh, prestressed cable pipes; measure the diameter of rebar, ...

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- Evaluation of moisture and salinity in structures.

Previous studies for GPR applications mainly relied on the analysis of reflected signals to evaluate the medium through which the wave travels. This method requires the presence of a reflector and its location. This leads to a number of difficulties such as: inability to accurately determine the depth of the reflective surface; the reflector is too deep; the contrast of the reflector is too low; or maybe the reinforcement density of the structure is too dense. These factors make reflected waves very difficult to detect for analysis. Therefore, recently a number of studies exploiting GPR direct waves to evaluate the physical properties of materials have also been performed [3-9]. However, the results of these studies are still scattered and incomplete. The evaluation of the effect of a dielectric constant gradient in the material on GPR measurements as well as the comparison and evaluation of the survey depth of the GPR direct wave with theoretical formulas and experimental results has not been studied.

In the author's previous experimental studies, conducted on sand materials and concrete materials, the effects of moisture gradient on the GPR direct wave has also been observed. However, the law of gradient in sand and concrete materials has not been accurately described. Therefore, the results of this experimental study only qualitatively confirm the influence of the moisture gradient on the GPR direct wave and have not quantified the survey depth of the direct wave.

In this paper, the author conducts research by the simulated phase to confirm the effects of a dielectric constant gradient on the GPR direct wave and to quantify the survey depth of the GPR direct wave with different antenna frequencies.

2 GPR direct wave

The propagation of electromagnetic waves radiated by an antenna, placed near the interface between the two medium allows the generation of direct waves (surface waves) [10-12]. According to the Fresnel principle, these direct waves are made up of an infinite number of Fresnel waves travelling around its orbit [13]. That means that the direct wave is always affected by some layer below the surface where the Fresnel wave travels and its thickness can be determined. The propagation depth of the direct wave depends on the parameters of the propagation medium and the frequency of the signal being sent. This depth represents the potential application of the direct wave for surveying construction structures. Berktold et al. [14] have shown that it is possible to evaluate changes the water content in soil at depths ranging from half the wavelength to one wavelength of the transmitted signal. Van Overmeeren et al. [15] give an estimate of the survey depth of the direct wave based on the concept of "Fresnel zone" [16] as follows:

$$h_p = \sqrt{\frac{\lambda d}{2}} \tag{1}$$

where:

h_p: the survey depth of the wave direct (depth of penetration)

d : the distance between the transmitting antenna (T) and the receiving antenna (R).

λ : the wavelength in the material is caculated by formule (2)

$$\lambda = \frac{V}{f} \tag{2}$$

with : V : speed of the wave travelling through the material;

f: frequency of the wave travelling in the material, it is calculated by formula (3) [17] :

$$f = \frac{f_0}{\sqrt{\frac{2}{1+\frac{1}{\varepsilon_r'}}}} \tag{3}$$

with : f_0 : centre frequency of antenna

ε_r' : Dielectric constant

This means that for a 1.5 GHz antenna, the distance between T and R is 20 cm, the depth of investigation in concrete with a dielectric constant of 10 (saturated concrete) is about 9.2 cm and in concrete with a dielectric coefficient of 5 (dry concrete) is about 10.7 cm.

3 Simulation of propagation in concrete with a gradient of dielectric constant

To do this, 2D simulations with GPRmax software were performed on two models with different gradients of dielectric constant and with the antenna with center frequencies of 1.5 GHz and 2.6 GHz, respectively.

3.1 Modelling

Two gradient models were simulated. The simulation work starts from a homogeneous model (with a dielectric constant of 5) and gradually integrates layers with varying dielectric constants to a depth of 20cm. Each integration adds 5 layers, i.e. 1 cm more. The thickness of each layer is 2 mm and the step of the dielectric constant is 0.05 for gradient model 1 and 0.15 for gradient model 2. Figure 1 diagrams the two simulated gradient models. A linear rule for increasing dielectric constant with depth is used to simplify simulation.

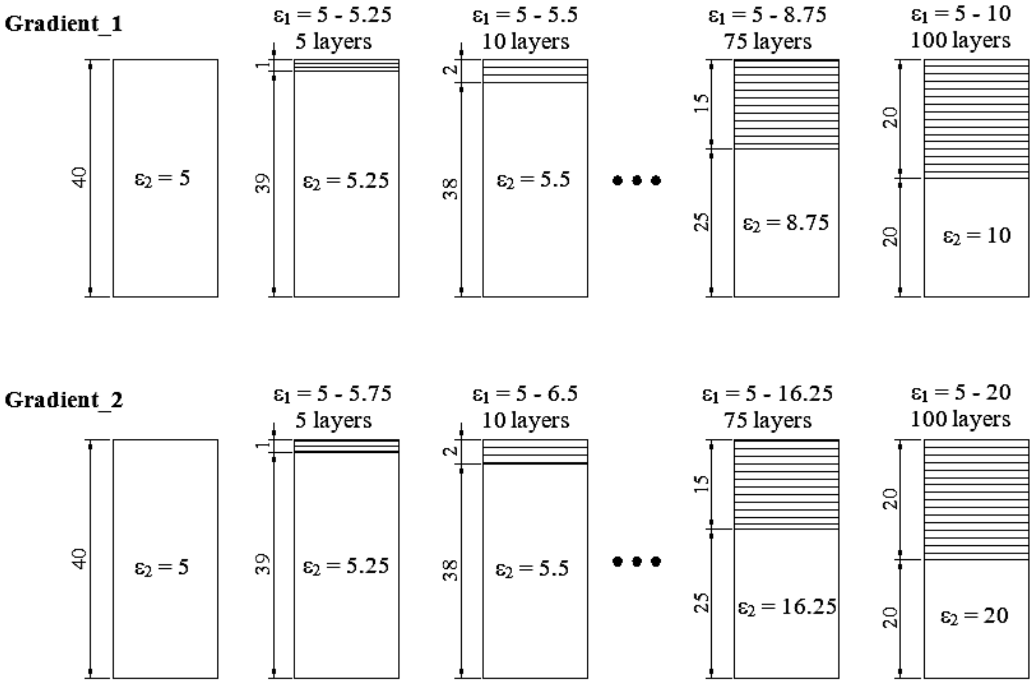

Fig. 1 – Diagram of two dielectric constant gradient models used in the simulation

3.2 Data processing

Analysis of the data is based on the calculation of the propagation velocity of the direct wave in the Wide Angle Reflection and Refraction (WARR) measurement configuration. These velocities are calculated from the slope of the linear relationship between the measured distance and the arrival time. This velocity is calculated for each instance of each gradient model. Hence 20 cases in each gradient model were studied.

The velocity of the direct wave is then extracted from the linear relationship between the measured distance and the arrival time and expressed in term of the thickness of the gradient layer.

Figure 2 is an example of the signals received in the case of a medium with a gradient in dielectric constant. A sharp attenuation of the direct signal can be observed. However, these signals can still be exploited to estimate the propagation velocity of a direct signal.

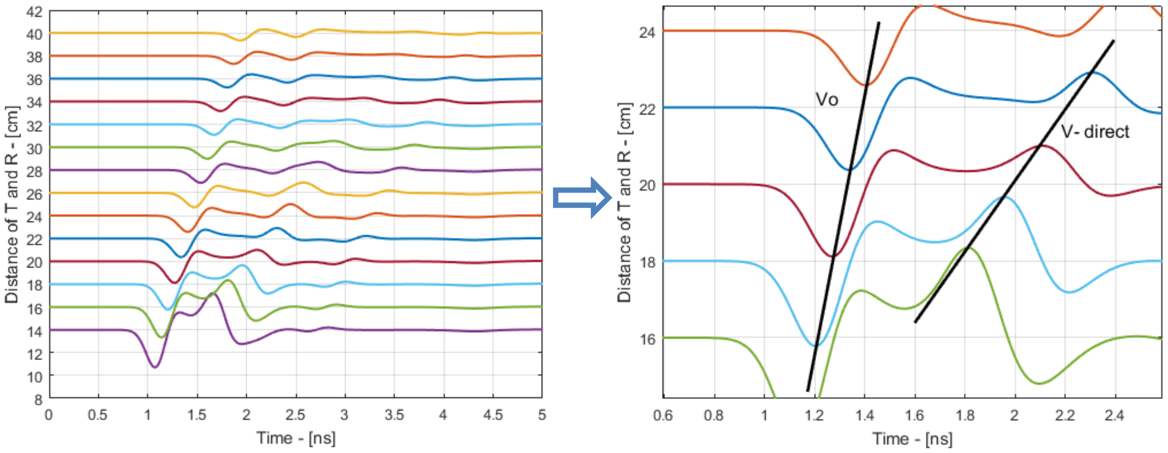

Fig. 2 – The received signal of the WARR measurement on concrete

Simulation in the case of thin gradient layers (2mm) show the absence of multi-reflection signals onthe reflective surfaces between layers. Indeed, figure 3 shows the instantaneous image at 1.75 ns propagation time, without the appearance of reflected signals and wavefronts, which is equivalent to what is observed in the case of wave propagation in homogenous medium. This is possible by reducing the thickness of the layers as well as the difference of dielectric constant between the layers.

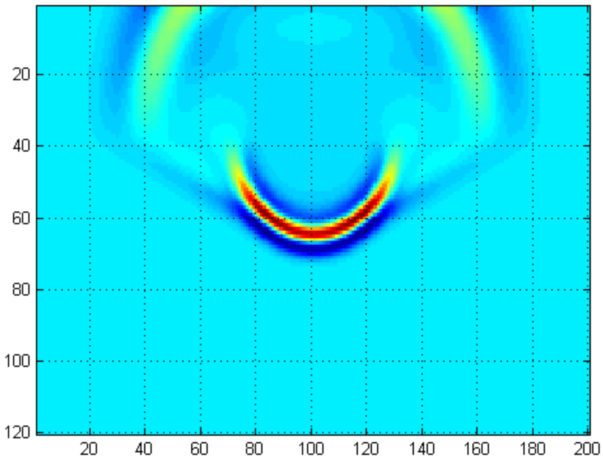

Fig. 3 – Instantaneous image of electric field in simulated space at 1.75 ns (thickness of gradient layer is 10 cm)

4 Analysis of simulation results

The simulation results are shown in figures 4 to 6. Each curve represents the change of the velocity as well as the dielectric constant with the thickness of the gradient in the case of a transmitting antenna with a center frequency of 1.5 GHz (figures 4 and 5), and in the case of a transmitting antenna with a center frequency of 2.6 GHz (figure 6). Note that it is very difficult to determine the extreme points of the direct signals at small gradient thicknesses (less than 4 cm), so this information is not shown in the figure.

In the case of the antenna with a center frequency of 1.5 GHz, the velocity curves show a decrease in velocity and a corresponding increase in the dielectric constant with the thickness of the gradient layer and this continues until the thickness of the gradient is about 10 cm for gradient 1 and 9 cm for gradient 2. After this thickness, increasing the thickness of the gradient layer did not have any effect on the change in velocity and dielectric constant measured by the signal of the direct wave.

In the case of the antenna with a center frequency of 2.6 GHz, from 4 cm to 8 cm we observe a sharp decrease in velocity and a corresponding increase in dielectric constant. Similar to the case of the antenna with a center frequency of 1.5 GHz, the measurements are stable from a certain thickness of the gradient layer, in the case of gradient 1 this thickness is about 8 cm.

These simulations show the stability of the velocities starting from a depth of 8 – 10 cm, which may be consistent with the explorable depth or sensitivity of this wave. However, these simulations should be used with caution because the simulations are performed without taking into account the size of the transmitting antenna as well as the receiving antenna. Nevertheless, these results are very close to those calculated from hypothetical theoretical formulas such as: the survey depth of the direct wave around the length of the wavelength (transmission in the material) i.e. is about 10.7 cm for the antenna with a center frequency of 1.5 GHz and a concrete with gradient 1; 9.4 cm for the antenna with a center frequency of 1.5 GHz and a concrete with gradient 2; and 6.2 cm for the antenna with a center frequency of 2.6 GHz frequency and a concrete with gradient 1. One difference should be noted for the antenna with a center frequency of 2.6 GHz, because the estimated depth is 8 cm i.e. 1.3 times its wavelength. However, if we use formula (1), we find that these results are quite close to those estimated by the simulations. Indeed, for the antenna with a center frequency of 1.5 GHz, the calculated depth according to the formula is about 10.34 cm for gradient 1; 9.4 cm for gradient 2 and about 7.87 cm for the antenna with a center frequency of 2.6 GHz in case of gradient 2, this is a very small error from the numerical simulation results.

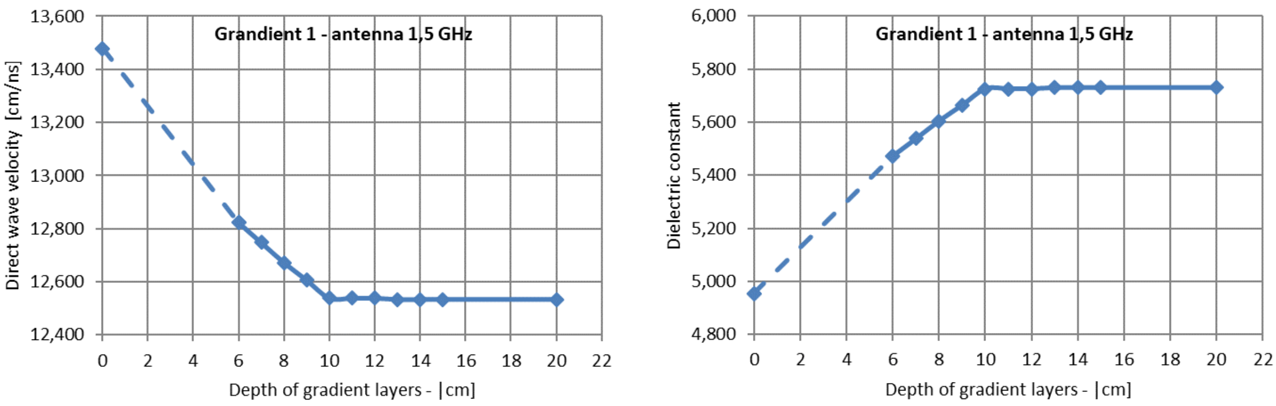

Fig. 4 – Direct wave velocity (left) and dielectric constant (right) dependent on layer thickness, in case of gradient 1 and the antenna with a center frequency of 1.5 GHz

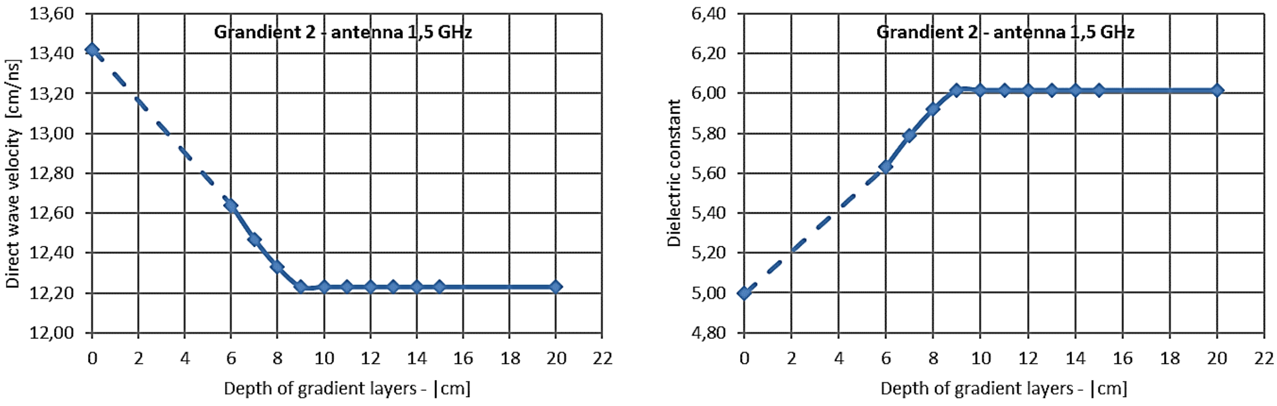

Fig. 5 – Direct wave velocity (left) and dielectric constant (right) dependent on layer thickness, in case of gradient 2 and the antenna with a center frequency of 1.5 GHz

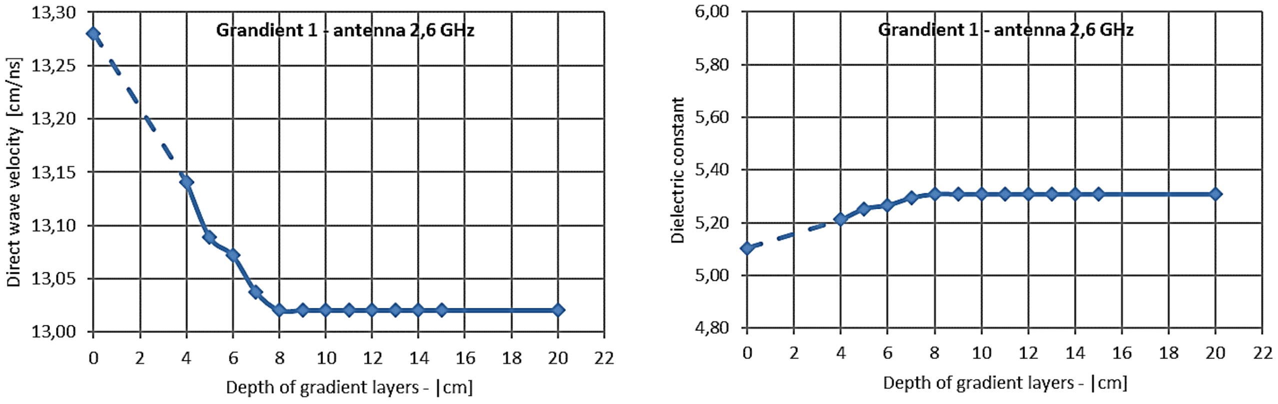

Fig. 6 – Direct wave velocity (left) and dielectric constant (right) dependent on layer thickness, in case of gradient 1 and the antenna with a center frequency of 2.6 GHz

5 Conclusion

2D numerical simulation based on GPRmax software was performed for the purpose of studying the effect of dielectric constant gradient on GPR direct wave velocity and determining the influence depth of direct wave in concrete. Two gradient models have been established with linear laws of dielectric constant with respect to material depth. Research has shown that the direct wave velocity is not a constant but varies depending on the thickness of the gradient layer. Increasing the gradient layer thickness results in a drop in velocity to a thickness of about 9 – 10 cm for the antenna with a center frequency 1.5 GHz and about 8 cm for the antenna with a center frequency 2.6 GHz. These results are consistent with the theoretical formula based on the concept of Fresnel zone, which shows that it is possible to study and evaluate concrete materials having a dielectric constant gradient by changing the antenna frequency or the distance between the transmitting antenna and the receiving antenna. At the same time these results also allow to confirm the surveyable depth of GPR direct wave and its potential application to concrete structures. However, more experimental campaigns on concrete are needed to investigate the depth of influence of GPR direct wave corresponding to the frequencies, measuring distances, and moisture content of the materials. And after non-destructive measurements, it is also necessary to perform destructive analyzes to confirm the theoretical, simulated and experimental results.

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