Time-Domain Modeling of Radar Assessment of Concrete: a Parametric Study

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***Abstract*— We are investigating the radar as a non-destructive technique to detect early-stage flaws and reinforcement in concrete structures. In this paper, we simulate the ground-penetrating radar (GPR) assessment of concrete structures using three-dimensional (3D) finite-difference time-domain (FDTD). The discussion focuses on the evaluation of the performance of GPR in assessing dispersive and heterogeneous models of concrete structures. The ability to detect flaws and reinforcement using bow-tie antennas for transmitting and receiving is investigated. Simulations are carried out to examine the influence of dispersion and heterogeneity on GPR measurements and its influence on spatial dispersion using various types of concrete characterized by low/high-performance, and ramdonly created heterogeneity.**

***Index Terms*— FDTD, GPR, Non-destructive testing.**

I. Introduction

DETERIORATION and distress mechanisms of the concrete infrastructure are active under the surface and cannot be accurately assessed by visual inspection. Periodic condition assessment of the concrete infrastructure results in better preventive and/or corrective planning, which helps preserve its integrity and reduce its life-cycle costs. The radar method is a very effective technique for investigating the integrity of concrete structures thanks to technological advancements over the past decade [1]. However, GPR measurements in structures which are only accessible from one side have some limitations and the method must be optimized to detect a specific target considering the physical characteristics of concrete by selecting the appropriate antenna type, antenna frequency, and antenna configuration. Therefore, the complex design of GPR assessment can be aided by using numerical simulation techquines that provides the eletromagnetic field behaviour when the antenna is interacting with a concrete slab. Three-dimensional finite-difference time-domain (FDTD) simulations of the assessment of lossless and lossy soils are reported in [2] and [3], respectively. The influence of heterogeneity on GPR measurements is examined in [4]. In this paper, we present the methodology and results from three-dimensional (3-D) FDTD modeling of propagation and scattering of the electromagnetic pulse assessment of heterogeneous and dispersive model of concrete, and the backscatter response of voids, fractures and buried conductors.

II. Summary of concrete dielectric properties

The concrete may be treated as a complex dielectric composed of inorganic material in the dry state with internal free water. The complex permittivity of water changes widely in the frequency bands used in GPR, (from short waves to the millimeter wave band). Consequently, the complex permittivity of concrete is greatly affected by its water content. The concrete can be visualized as a three-phase mixture consisting of solid particles and air which have a real dieletric constant and saline water which has a complex dielectric permittivity. In order to obtain the dieletric properties of concrete, dielectic models are necessary to determine the effective dielectric properties of a heterogeneous mixture of two or more substances of known permittivities. Factors influencing the effective permittivity of a mixture include the permittivities of the individual substances, their volume fractions, spatial distribution and shapes of the constituents and their orientation relative to the electric field vector of the incident electromagnetic waves. To simulate a more realistic concrete model, we use two different approaches:

1) The model proposed by Halabe [5] that deals with complex conductivities instead of complex permittivities;
2) Randomly created subsurface heterogeneities.

We performed simulations with two types of concrete; the first is a high-performance concrete, with low porosity and water-cement ratio and the second is a concrete characterized by bad curing. With modern concrete technology one can produce a concrete with low porosity. This type of concrete is characterized by a low water-cement ratio and use of additions and admixtures together with aggregates. But even if the composition is optimal and the compaction is well done something can go wrong through improper curing, which can determine the concrete's quality. Table 1 shows the properties of the two types of concrete mentioned above.

TABLE I
Characteristics of concrete

Concrete	Type 1	Type 2
Degree of saturation	0.2	0.35
Salt content of water (ppm)	60	65
Temperature (Celsius)	20	20
Porosity of mixture	0.08	0.2

According to the discrete grain size model the permittivities of the two types of concrete can be described using the Debye parameters shown in Table II (obtained using a polynomial function) considering the conductivity for the central frequency of (1.5 GHz). Where ϵ_∞ is the permittivity in the high frequency limit and ϵ_s is the static, low frequency permittivity.

The first conclusion that can be drawn is that it is more difficult to find any kind of inclusions in concrete structures

TABLE II
ELECTRICAL CHARACTERISTICS OF CONCRETE

Concrete	ϵ_∞	ϵ_s	$\tau_D(ns)$	σ (S/m)
Type 1	3.857	5.113	0.525	0.031
Type 2	3.981	6.398	0.033	0.182

affected by bad curing due to its higher conductivity and permittivity. The material loss will affect the depth range of the assessment. Using the radar equation for a central frequency of 1.5 GHz and a transmitted bandwidth of 2.5 GHz, and considering targets with a high loss, the depth range for concrete of type 1 and 2 are $R_1 = 1.10m$ and $R_2 = 0.19m$ respectively. The resulting depth resolution is accurate to 2.4 cm for concrete of type 2 (approximately 12.6% of the depth versus 1.73% of the depth in concrete of type 1).

III. Time-domain simulation results

In the following, we consider a bow-tie antenna shielded with a metal casing. In the FDTD analysis, the slanted edges of the bowtie antenna are approximated using staircasing with a $\lambda_{cf}/95$ spatial-grid resolution. The transmitting and receiving antennas based on the GSSI model described in [6] (the GSSI antennas are trade-secrets; in order to find an antenna of good quality and eletrical size compared to the original antenna, multi-objective genetic algorithms where used [7]) are placed side-by-side immediately above the concrete. The targets to be detected are buried conductors and air/water filled fractures.

A. Dispersive case

Figure 1 shows the FDTD scenario of the simulation. The depth d of the reinforcement bar is $15cm$ with radius $r = 1.25cm$ spaced a distance $s = 5cm$. The simulation was

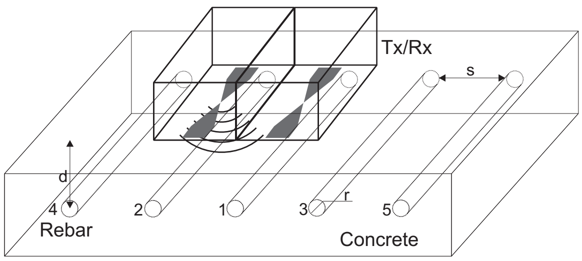

Fig. 1. FDTD simulation scenario.

performed with the goal of studying detection of reinforcement bars, air and water filled fractures in different types of concrete. The 3D domain used had $150 \times 150 \times 120$ cells with $\Delta = 2.1mm$ and $\Delta t = 4ps$. Non-orthogonal grid was used to produce a fine mesh in the antenna. The type 2 concrete produced a reflected wave that normally cannot be detected by measurements. This unexpected result can be explained by the fact that the radar equation doesn't account for the dispersion effects of the specimen.

B. Heterogeneous case

The influence of heterogeneity on GPR measurements is examined next. The forward modeling results presented in this

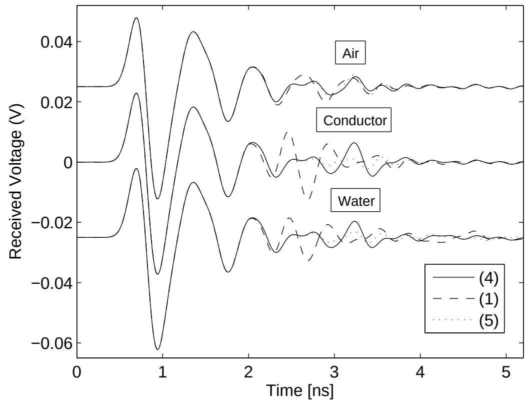

Fig. 2. Results for concrete Type 1.

paper incorporate heterogeneity by replacing the traditional homogenous spatial regions with a statistical distribution of physical properties. A mean electrical permittivity value of 6 and conductivity 0.01 S/m were used and standard deviations (SD) ranging from 0.05 to 0.25 were applied. Each distribution is then modified by four different SDs. The same random numbers were applied to modify the properties in the X, the Y, then the Z direction to simulate one dimensional changes in properties. The same procedure was used for two and three dimensional changes. The results have shown that even the smallest SD can increase the clutter and consequently the difficulty of detection near the surface. Visible reflections from layers and delayed resposes from the targets were also observed in two an three dimensional changes, respectively.

IV. Conclusion

Time-domain numerical experiments have been performed to analyze the GPR assessment of dispersive and heterogeneous concrete structures. The numerical simulation results shown may help to minimise the overall cost of an investigation and to increase the likelihood of carrying out fully effective maintenance and repair in concrete structures.

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