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Time-lapse monitoring of internal alteration of a concrete structure using ground penetrating radar

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HIGHLIGHTS

- A novel approach to detect internal structural alterations.
- Ground penetrating radar used to assess civil infrastructures.
- Destructive and non-destructive measurement of concrete wall damage.

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ABSTRACT

Early recognition of concrete deterioration is an important engineering task with many associated monitoring challenges. Ground penetrating radar (GPR) is an important non-destructive testing tool commonly used by engineers to locate internal reinforcement and voids within concrete. However, the general standard of interpreting subsurface conditions from one GPR survey is insufficient for determining the rate and extent of concrete deterioration. Differences in the amplitude response of reflected radar waves within a subsurface region, as measured by repeat (4D) GPR surveys over calendar time, provide a more robust indication of changes in the condition of concrete material. Variations in the 4D amplitude response may be associated with alteration (moisture content or pore-space) in material properties (dielectric permittivity, electrical conductivity). We present a 4D GPR monitoring study of the internal deterioration of a purpose-built reinforced concrete wall subjected to increasing mechanical load until reaching structural failure (107.4 kN). At 10 kN load increments, we scanned the wall surface with a 1.6 GHz GPR system and computed difference data sets that highlight changes in the 4D amplitude response. Significant 4D anomalies were observed between the 60 kN and 100 kN data sets, including spatially distributed alteration zones co-located with the wall failure location. We interpret these zones as experiencing stress-induced porosity reduction and/or an increase in micro- or macro-fracturing. Overall, this work demonstrates that 4D GPR is useful for highlighting regions of 4D strain variations, and is thus an important monitoring tool for early recognition of concrete deterioration.

1. Introduction

Modern society is highly reliant on major civil infrastructure including tunnels, subways, bridges, dams and pipelines for the storage and movement of transportation, water and waste supplies. Civil infrastructure monitoring and non-destructive testing are important undertakings for structural engineers aiming to determine infrastructure condition. Observing the development of structural weakness as early as feasible is also essential, as this assists with prioritising locations requiring prompt maintenance, repair or replacement. However, there are significant challenges associated with efficiently monitoring structural change and deterioration of infrastructure over calendar time, particularly with defining changes in condition beneath visible surfaces. Overall, civil engineers are still investigating cost-effective approaches for large-scale and non-invasive infrastructure monitoring.

Geophysical technologies such as single-channel ground penetrating radar (GPR) have proven to be an essential infrastructure

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assessment tool capable of providing information on subsurface conditions. GPR data contain reflections (and other types of scattering) from contrasts in dielectric properties at boundaries between different materials, such as steel reinforcement and concrete or an air void and concrete. Common applications of single-channel GPR to engineering investigations include locating rebar [1–5], voids and cavities [6–8], and regions of moisture within concrete structures [9,10].

GPR also has been applied as a time-lapse (4D) tool for monitoring subsurface changes in fluid distribution over calendar time [11–13], subsurface hydrocarbon plumes for environmental remediation purposes [14], the reaction of concrete reinforcement to intrusive chloride contamination [15], the development of cracks within historical buildings [16], and the leaking of water from buried pipes [17]. However, the use of single-channel GPR for monitoring changes in the subsurface condition of solid continuous (non-hollow) concrete with little-to-no steel reinforcement (e.g., non-hollow concrete tunnel linings) over various increments of increasing applied load, has yet to be thoroughly investigated.

Previous investigations have used 4D GPR analyses for monitoring solid concrete civil infrastructure. For example, Orlando et al. [18] describes the application of 4D GPR for evaluating the deformation of a reinforced hollow concrete pier, and compares the results before and after inducing failure. The authors acquired GPR data using a bistatic 2.0 GHz antenna simultaneously in two orthogonal orientations along parallel transects. The thickness of the column's concrete lining and the vertical resolution of the GPR wave were both approximately 6 cm. When comparing pre- and post-failure GPR time slices, no significant variations were observed in measured amplitudes; similarly, no continuous micro- or macro-fractures or cracks were noted. While spatial variations in the GPR propagation velocity and reflection amplitudes were more significant in the post-failure survey, interpreting these changes proved challenging due to the complexity of GPR diffractions caused by internal reinforcement as well as multiple reflections generated by air space within the columns. However, comparing the normalised difference of amplitude spectra revealed an increased variation of high-frequency spectral components (2.0–3.5 GHz) in an unprotected zone, which the authors attributed to the loosening of the rods from the concrete and the presence of strain-induced micro-fracturing. This example suggests that structural failure induced variations in the dielectric and/or electrical conductivity properties and thereby the GPR wave propagation velocity and attenuation behaviour. However, the limited number of pre-failure snapshots provided no evidence as to the sensitivity of 4D GPR data to material property changes leading up to failure and therefore its usefulness for concrete monitoring investigations (though this was not a specific investigation goal).

A main goal of this paper is to demonstrate the utility of 4D GPR analyses for highlighting and monitoring regions of GPR amplitude change within civil infrastructure associated with internal deformation processes. Rather than examining a curved concrete tunnel lining in an actual infrastructure scenario, our tests involve constructing, stressing and ultimately breaking a model concrete wall sample of dimensions 170 × 60 × 30 cm^3 in a controlled laboratory setting. We examine whether deformation induced in a concrete wall undergoing a test strain-loading cycle (up to material failure) will alter material dielectric properties to an extent measurable by 4D GPR analysis. While applying strain within a linear elastic regime is unlikely to induce measurable changes in dielectric properties, concrete experiencing high strains and non-linear anelastic behavior may sufficiently alter dielectric property values to be detectable as 4D GPR anomalies. In particular, GPR waves propagating through volumes of highly strained material could be strongly influenced by micro- and/or macro-fracturing, which could cause significant variations in measured 4D GPR amplitudes (and potentially 4D travel times) [19]. Ideally, a successful demonstration should help motivate the use of 4D GPR analyses for locating and monitoring regions within solid concrete infrastructure experiencing high rates of strain-induced mechanical alteration.

The paper begins with a short discussion on the factors affecting GPR wave-propagation velocity in non-magnetised materials (i.e., concrete). We highlight our experimental methodology, including the schematic stage, the preparation of the concrete test wall, the applied dielectric laboratory tests, the approach for applying a load, the GPR data acquisition procedure, and the applied Baldwin Engineering tests. We then present our test results and a short discussion on our interpretation of observed 4D GPR anomalies.

2. Factors affecting GPR wave propagation

GPR data are acquired as individual traces that form an amplitude time series. Acquiring numerous GPR traces along one or more offset transects leads to a 2D radargram or a 3D radar volume. However, because the structures being investigated have physical dimensions of length, one needs to convert GPR data from time to depth (T2D) prior to estimating the distance between observed features. Although T2D transformation parameters can be constrained from GPR data alone, a dielectric analysis of the host material [20] using a parallel plate or loaded transmission line instrument [21] generally provides for a more accurate measurement of EM physical properties.

Performing a T2D conversion requires calculating the GPR wave propagation velocity. The complex EM wavenumber, k, (used to define a plane-wave solution to Maxwell's Equations governing EM wave propagation [22]) is given by:

$$k^2 = \omega\mu(\epsilon\omega + j\sigma), \tag{1}$$

where ω is angular frequency, μ is complex magnetic relative permeability, ϵ is dielectric constant, $j = \sqrt{-1}$ is the complex unit, and σ is conductivity. Complex quantities ϵ and μ have associated real (ϵ', μ') and imaginary (ϵ'', μ'') contributions:

$$\epsilon = \epsilon_0(\epsilon' - j\epsilon''), \tag{2}$$

$$\mu = \mu_0(\mu' - j\mu''), \tag{3}$$

where ϵ_0 and μ_0 are the permittivity and permeability of free space, respectively. Following the nomenclature in Stratton [22], we use $|k| = |\alpha + j\beta|$, where α is related to the propagation velocity and β is related to attenuation, as we show below. We write the square of complex wavenumber, k^2, as:

$$k^2 = \alpha^2 - \beta^2 + j2\alpha\beta. \tag{4}$$

Assuming a non-magnetic material (i.e., $\mu' \approx 1$ and $\mu'' \approx 0$), we rewrite Eq. (1) as

$$k^2 = \epsilon_0\epsilon'\mu_0\omega^2 - j\left[\mu_0\omega\sigma' + \epsilon_0\epsilon''\mu_0\omega^2\right]. \tag{5}$$

Equating the real and imaginary contributions from Eqs. (4) and (5) yields

$$\alpha = \left[\frac{\mu_0\epsilon_0\omega^2}{2}\left(\sqrt{(\epsilon')^2 + (\epsilon'')^2} + \epsilon'\right)\right]^{\frac{1}{2}}, \tag{6}$$

and

$$\beta = \left[\frac{\mu_0\epsilon_0\omega^2}{2}\left(\sqrt{(\epsilon')^2 + (\epsilon'')^2} - \epsilon'\right)\right]^{\frac{1}{2}}, \tag{7}$$

where real component α determines the effective EM wave propagation velocity