DETECTION OF FRACTURES IN CONCRETE BY THE GPR TECHNIQUE

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Abstract: The paper examines the detection of fracture in concrete by the ground penetration radar technique. The experiments were conducted on a large concrete slab of 3 m length, 3 m width and 4 m high. An inclined crack was induced in the slab at 3.4 m depth by hydraulic fracture. The GPR tests were performed from the top of the slab for different crack widths and different conditions of the crack (air filled and water filled). The preliminary results of this study shows that the GPR technique can detect deep cracks in concrete.

Introduction : The majority of severe cracking in concrete dams is due to climatic conditions. During setting and hardening of fresh concrete, the heat of hydratation substantially increases the internal temperature of the concrete which cools over time. The thermal gradient between the center of the dam and its surfaces provoke nonuniform volumetric changes in the concrete. When thermal stresses exceed the tensile strength capacity of the concrete, cracks form in the dam which can lead to further deterioration of the structure. Climatic conditions continue to contribute to the damage over the service life of the dam long after the effect of heat hydratation has dissipated.

The Daniel-Johnson Dam located in Quebec, Canada, is a typical example of a large dam that has undergone thermal damage. This dam was constructed between 1961 to 1968 and is considered as the biggest multiple arch dam in the world with a height of 214 m and a crest length of approximately 1314 m. Tow parallel inclined (10º) cracks appeared in one arch of the dam just after construction.

Hydro-Québec, the owner of this dam, would like to identify a non-destructive testing method that is able to detect the cracks in the dam and to find a way of mapping the detected fractures in 3D in order to apply this to the dam management plan. A research project was thus recently initiated by the Research Group on Nondestructive Testing and Instrumentation (University of Sherbrooke, Québec, Canada) with the collaboration of the Concrete Research Laboratory of Hydro-Québec to evaluate the ability of some NDT testing techniques to correctly detect and map fractures in mass concrete structures. This paper deals with the application of the Ground penetrating radar (GPR) technique to fracture detection and present the preliminary results obtained in this study.

Nondestructive detection of fractures in materials : Recent advances in theory and in available NDT technologies have greatly increased our ability to detect fractures at depth and to characterize their properties. NDT fracture detection methods can be divided into three distinct scales [1]: (1) large scales associated with surface measurements, (2) intermediate scales associated with surface-to-borehole and borehole-to-borehole measurements, and (3) small scales associated with measurements made on the material immediately adjacent to a borehole. Most of these methods (seismic, electromagnetic, electrical, well log methods..) detect fractures indirectly. Typically, data collected with each detection method (e.g., seismic travel times) must be inverted to yield estimates of local material properties (e.g., seismic velocities). Normally, these material properties are not fracture properties (e.g., fracture density). Instead, the fracture properties must be indirectly deduced from the material properties. Fracture detection methods also rely on the fact that fractures are thin compared to their lengths; that is, they are essentially two-dimensional anomalies. In addition, because they are commonly organized into one or more sets, fractures commonly impose some anisotropy in physical properties of the material. This anisotropy may be an important characteristic for fracture detection, especially when the anisotropy is simple.

The ground-Penetrating Radar technique : Ground-penetrating radar (GPR) uses electromagnetic energy to obtain information about the subsurface. In principle, GPR is similar to reflection seismic techniques. The radar produces a short pulse of high-frequency (10- to 2000 MHz) electromagnetic energy, which is transmitted into the ground. Propagation of the radar signals depends on the electromagnetic properties of the material, mainly the dielectric permittivity (ε) and electrical conductivity (σ). Where these properties change abruptly in the subsurface (Fig. 1), part of the energy is reflected back to the surface. The reflection strength R is given by :

$$R = (\varepsilon_{r1}^{0.5} - \varepsilon_{r2}^{0.5}) / (\varepsilon_{r1}^{0.5} + \varepsilon_{r2}^{0.5}) \qquad (1)$$

where ε_{r1} is the relative permittivity of medium 1 and ε_{r2} is the relative permittivity of medium 2.
The propagation velocity (V) in a medium of a relative dielectric permittivity ε_r is :

$$V = C / \varepsilon_r^{0.5} \qquad (2)$$

where C is the electromagnetic wave propagation velocity in air (C = 0.3 m/ns)

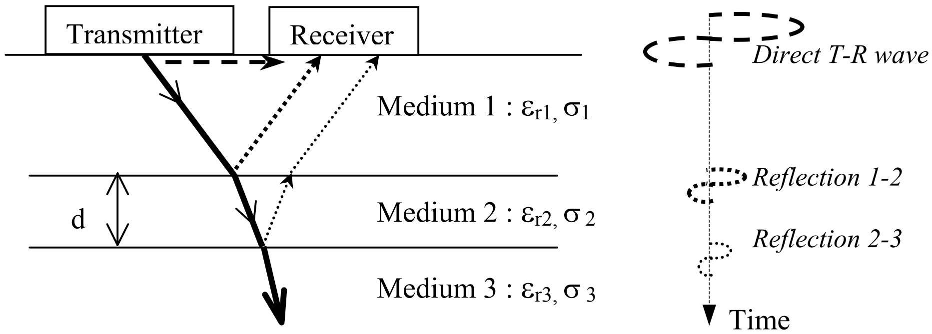

Figure 1 : Reflection and transmission of electromagnetic waves at interfaces

Sensitivity and resolution are two terms that are often used in NDT to describe a technique's ability to locate and characterize the dimensions of flaws such us cracks in a medium.
Sensitivity is the ability of the technique to detect small discontinuities and is affected by the signal-to-noise ratio (S/N). This ratio is a measure of how the reflected signal from the defect compares to other background reflections (categorized as "noise")). The absolute noise level and the absolute reflection strength from a defect depends on a number of factors :

- The frequency, bandwidth and efficiency of the GPR antennas (sensitivity generally increases with higher frequency (shorter wavelengths)),
- The inherent noisiness of the medium and,
- The reflectivity of the defect which is dependent on the contrast between its electromagnetic properties and those of the medium (the reflectivity of a water filled crack will be higher than that caused by an air filled crack), its size, shape (surface curvature and roughness), orientation and location with respect to the incident energy. This reflectivity is generally considered as weak if $-0.2 < R < 0.2$, medium if $-0.35 < R < -0.2$ or $0.2 < r < 0.35$ and strong if $-1 < R < -0.35$ or $0.35 < r < 1$.

The resolution of a GPR system relates to its ability to distinguish between two reflections induced by two interfaces that are close together within the material (fig. 1). In practice, this distinction is possible when the distance (d) between the two interfaces is at least equal to the quarter of the wavelength [2]. Hence, resolution increases as the frequency of the electromagnetic waves increases and high frequencies GPR systems are required for this purpose.
Another important consideration when applying the GPR technique to subsurface investigation is the exploration depth. Electromagnetic waves are more sensitive to water content of concrete than seismic waves and this limit their probing range. Water has two effects on the attenuation of electromagnetic waves; first, water contains ions which contribute to bulk conductivity. Second, the water molecule absorbs electromagnetic energy above 1000 MHz.
The simplest way to get estimates of exploration depth is to use the radar range equation (RRE) analysis [3]. However, this equation is considered to be too complicated for routine use by many users. The following simpler rule-of-thumb for estimating exploration depth is suggested by [3] :

$$D = 35 / \sigma \qquad (3)$$

Where D is the exploration depth (m) and σ is electrical conductivity in mS.m

This penetration depth is roughly inversely proportional to the first power of the conductivity of the material and decreases with increasing frequency. In highly resistive materials, penetration depth of about 100 m are regularly obtained for frequencies in the 20- to 100-MHz range [1]. In highly conductive medias such as saturated concrete, penetration depths are commonly only a few meters. For example, high-frequency radar (1000 to 2000 MHz) is regularly used in the investigation of roads and concrete bridge decks for rebars and voids detection, asphalt and concrete thickness estimation.

Experimental program : GPR investigations dealing with fractures detection in concrete are generally performed on slabs of approximately 0.20 – 0.3 m thickness. This is because most civil engineering infrastructures (ex. roads, bridge decks, tunnels) are constructed with concrete elements of these thicknesses.

In our study, a large concrete bloc of 3 m width, 3 m length and 4 m height was constructed to test the ability of the GPR technique to detect deep cracks in concrete. The concrete used was an ordinary Portland cement concrete with a compressive strength of 38 MPa at 28 days. The bloc was constructed in two steps (fig. 2) : in a first time, a certain volume of concrete was poured in the mould. The high of the poured concrete was 0.8 m at the south side of the bloc and 0.3 m at the north side of the bloc. This lead to a 9.46º inclined surface relatively to the horizontal plan. Seven days later, once this first poured concrete hardened, a small layer of sand and coarse aggregates (2 cm diameter) was spread on the surface to create a weakness area in the bloc. A second volume of the same concrete was then poured in the mould to obtain a bloc of 4 m high. The bloc was reinforced with 16 mm diameter steel bars which were fixed only on the four vertical sides of the bloc and at a distance of 5 cm from the surface.

The crack in the bloc was created by hydraulic fracture. Water was injected in the bloc by the aid of a 2 cm diameter water pipe introduced from the north side in the weakness area during the construction of the bloc. The water pressure used for this purpose was sufficiently high to create a crack at the interface between the concrete poured during the first step and the concrete poured during the second step. To prevent water leakage from the sides of the bloc, an imperviousness membrane was fixed vertically around the inclined surface of the concrete and at a distance of 20 cm from the surface.

The thickness of the crack created in the bloc is adjustable. To fix this thickness to a desired value, water is injected in the crack with a growing pressure. This water pressure lift-up the concrete volume above the crack. The value of this lift-up is measured with a set of four displacement transducers fixed at the north and at the south sides of the bloc (fig. 3). Once the crack thickness has reached the desired value, the concrete volume above the crack is blocked with a set of screw-jacks.

GPR measurements were conducted with a commercial GPR system (SIR 20) manufactured by Geophysical Survey Systems inc. using a 400 MHz center-frequency antenna. Radar data was collected with the antenna fixed at the center of the top surface of the bloc (fig. 4) and for different crack thicknesses (0.5, 1, 2 and 3 mm) and different conditions (air and water filled).

Results and discussion : Penetration depth of radar waves in concrete at 400 MHz was first estimated using equation (2). To do this, sixteen electrical conductivity measurements (Wenner technique) were conducted at a frequency of 97 Hz on the four vertical sides of the bloc. The average value of the apparent conductivity was 10.5 mS.m . However, in porous materials such as concrete, electrical conductivity increase with frequency. Soutsos et al. [4] showed that electrical conductivity at 400 MHz is about two times the conductivity measured at very low frequency. Thus, the electrical conductivity of the concrete investigated is approximately 21 mS.m at the GPR frequency used. This lead to a penetration depth of about 1.66 m.

Preliminary data analysis showed effectively that electromagnetic wave energy is very attenuated in the concrete and that the reflection from the crack was not visible, even in the case of a water saturated crack of 3 mm thickness. To improve the quality of the information in GPR signals (increase the signal-to-noise ratio), a low pass filter (25 – 100 MHz) was applied to the data as well as a linear gain.

Figure 3 gives typical GPR signals obtained in the case of a crack thickness of 0.5 mm and where this crack is air filled and water filled. The horizontal axis represent the two-way travel time of the radar wave and the vertical axis represent the amplitude. If we assume that the relative permittivity of the concrete is equal to 9, then the propagation wave velocity is 0.1 m/ns. At the center of the bloc, the crack is located at approximately 3.45 m from the top surface. The reflection on the crack must thus appears at 69 ns. Figure 3 show that some energy is effectively reflected back to the surface at approximately 65 ns. The reflection amplitude of air filled crack is negatively polarized whereas the reflection obtained in the case of water saturated crack is polarized positively and is less strong. The detection of the crack is possible in this case because the diameter of the antenna footprint (Fresnel zone, Fig. 4) at the crack depth is lower than the lateral dimensions of the crack (3 m * 3 m) and the reflectivity is maximal.

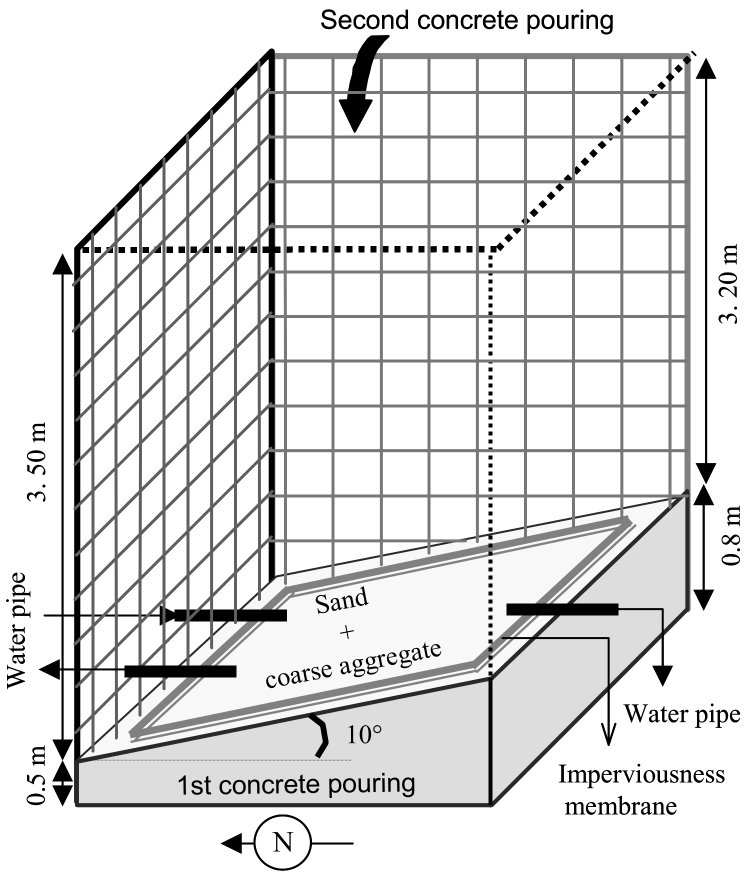

Figure 2 : Internal configuration of the bloc

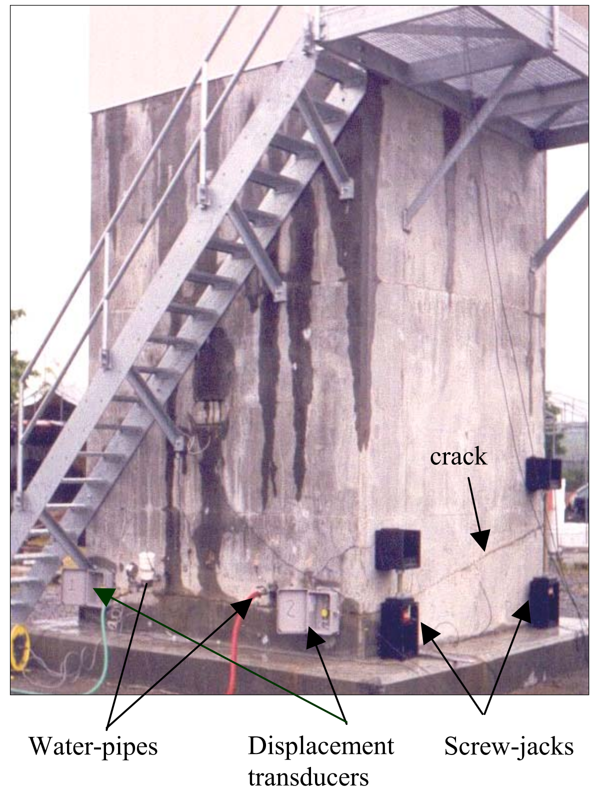

Figure 3 : External Instrumentation of the bloc

Figure 5 shows GPR reflection signals for a crack thickness of 2 mm. These signals were collected continuously for different situations and without data acquisition interruption: (1) crack filled with air, (2) water progressively filling the crack, (3) water progressively living all the crack and , (4) water progressively filling the crack again. It can be seen that the reflection amplitude on the crack increase progressively and is maximal during the last step of the experiment. The reflection amplitude at the beginning, in the case where the crack in empty, is not negative as supposed to be. This situation can be explained by the fact that the crack-lips were not entirely dry, as in the case of the third step of the experiment where the water leaves the crack.

Conclusions : The preliminary results reported in this paper indicate that the GPR technique can detect deep cracks with large lateral dimensions in concrete . Our investigations relative to this GPR application are still in progress. In particular, we are focusing our research on the effect of the crack thickness on the amplitude of the reflection as well as on the repeatability of the results.

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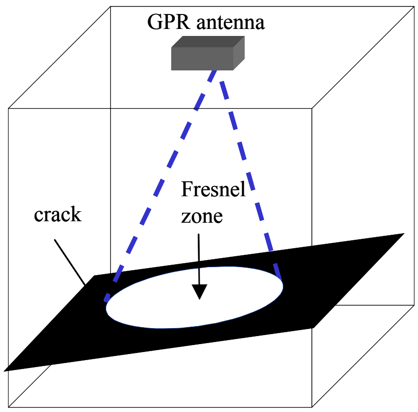

Figure 3 : The fresnel zone

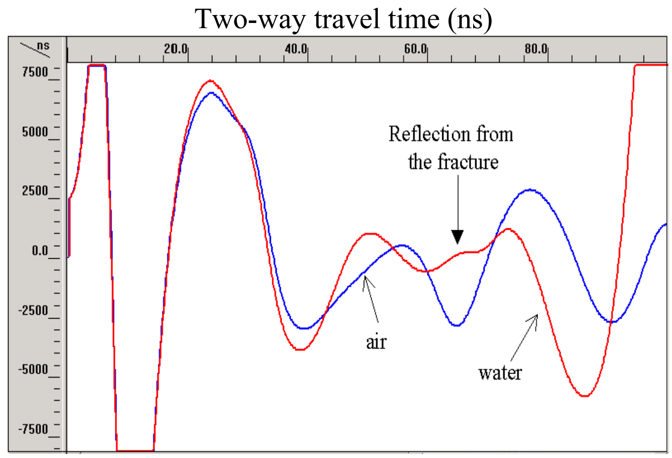

Figure 4 : GPR reflections on a water and air filled crack of 0.5 mm thickness

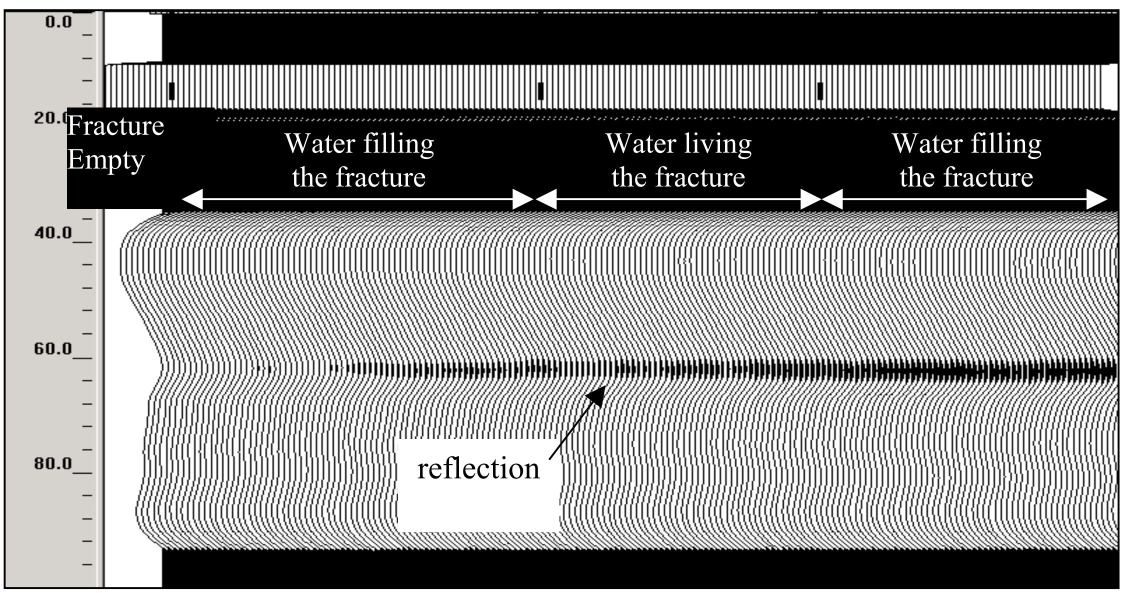

Figure 5 : GPR data obtained on a crack of 2 mm thickness

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