GPR: A NEW TOOL FOR STRUCTURAL HEALTH MONITORING OF INFRASTRUCTURE

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Abstract

Recent developments in acquisition methodology, data acquisition systems, post-processing software, and the availability of user friendly high-frequency antennas have enabled the GPR user to generate accurate three dimensional images of the interior of concrete structures.

Four case studies are discussed with emphasis on output that is readily understood by the non-specialist engineer. In the first two the results of traditional applications such as mapping reinforcing steel and post-tensioning cables are demonstrated.

The third case shows the results of a challenging void detection investigation, whilst the last one demonstrates for the first time that GPR can detect fibre reinforced polymer bars (FRP) embedded in concrete.

INTRODUCTION

The application of ground penetrating radar (GPR) for the investigation of concrete structures is well known and has been in widespread use for a number of years [1, 2, 3]. However, it has only become mature with the advent of digital data processing in the 1990s. Early applications included exploration and mining, archaeology, mine detection and military uses. Most commercially available systems were slow and cumbersome to operate and their use required a trained and experienced geophysicist. However, starting in 2001, when faster microprocessors become available, new and user friendly dedicated radar systems came to the market. The manufacturers rolled out task specific units creating a virtually new non-destructive testing (NDT) technique for engineering, construction, and infrastructure monitoring and management applications. Despite the relative obscurity of GPR outside of geophysics or electrical engineering departments, its use has been gaining ground steadily.

GPR is a real-time, non-destructive testing technique using high frequency radio waves that can yield data with very high spatial resolution (on the order of centimeters) and the data can be acquired rapidly. It uses high frequency radio waves to inspect the interior of concrete structures. Data collection is continuous, allowing scanning of a two-foot by two-foot (60 cm by 60 cm) area in 15 minutes or less, or capturing several kilometers of continuous data in a few hours.

Current applications for structural engineers most commonly include locating spacing and depth of reinforcing steel, post tensioning cables or anchors, measuring rebar cover, mapping voids, and clearing areas prior to cutting, coring and trenching [1]. GPR is a useful tool for seismic upgrades, road and bridge deck condition surveys, mapping delamination, or locating “lost” footings and/or utilities. Bungey [1] provides a comprehensive review on GPR testing of concrete.

Structural applications include addressing the integrity of the concrete itself, such as the presence of voids, cracks or chemical alteration. Due to the less well defined character of such features, GPR applicability is not always predictable on these projects and interpretation of the results depends on the specific site conditions and on the experience of the technical personnel [4]. Intrusive testing, such as drilling or coring, often accompanies GPR investigations in order to draw definitive conclusions [3, 4].

THEORY OF OPERATION

GPR uses high frequency pulsed electromagnetic waves (typically from 10 MHz to 2000 MHz) to acquire subsurface information. Electromagnetic waves travel at a specific velocity that is determined primarily by the electrical permittivity of the material. The velocity is different between materials with different electrical properties, and a signal passed through two materials with different permittivities over the same distance will arrive at different times. As the antennas are moved along a survey line, a series of traces or scans are collected at discrete points along the line. These scans are positioned side by side to form a display profile of the surveyed area [5].

The most common mode of GPR data acquisition is the reflection profiling method. In the reflection mode of operation, a radar wave is transmitted, received and recorded each time the antenna has been moved a fixed distance across the surface of the ground, in a borehole, or across any other material that is being investigated. In addition to surveys on land and ice, surveys can also be made in lakes and rivers with low conductivity water.

Signal penetration varies with the resistivity of the host material and the antenna frequency, and it can be more than 30 meters in materials having a conductivity of a few milliSiemens/meter [6]. However, penetration is commonly less than 20 meters in most soil and rock. Penetration in mineralogic clays and in materials having conductive pore fluids may be limited to less than 1 meter [5].

GPR EQUIPMENT

GPR equipment utilized for structural integrity assessment normally consists of a radar control unit, transmitter and receiver antennas, and data storage and/or display devices (Figure 1). The radar control unit generates synchronized trigger pulses to the transmitter and receiver electronics in the antennas.

The center frequency of commercially available antennas ranges from 10 to 2000 MHz. In general, lower-frequency antennas provide an increase in depth of penetration but have less resolution than higher-frequency antennas.

High frequency (500-2000 MHz) ground coupled antennas provide the best compromise between penetration and resolution in concrete settings. Most commercially available systems are portable, compact, user friendly, and function under a variety of environmental conditions allowing a great deal of operational flexibility (Figure 1). Air coupled horn antennas, on the other hand, allow data collection at high speeds (60 km/hr) and are ideally suited for highway pavement thickness measurements. They, however, sacrifice data quality for collection speed and, therefore, are not suitable for detailed structural investigations.

GPR systems are digitally controlled, and data are recorded digitally for post-survey processing and display. The digital control and display part of a GPR system generally consists of a microprocessor, memory, and a mass storage medium to store

Figure 1. GPR scanning of a bridge girder.

measurements. A small micro-computer (laptop or built in digital video logger (DVL)) and standard operating system is often utilized to control the measurement process, store the data, and serve as a user interface [5, 6]. Field data is generally saved for post processing, except in those cases where the data are to be interpreted immediately after recording.

DISPLAY AND INTERPRETATIONS

Radar data are either displayed as a cross section (line or B-Scan) or a plan map (grid or C-Scan). Grid scans are more readily understood by a non-specialist engineer (Figure 2). The results of the grid scan can be viewed both as cross sections and as plan view maps providing a quasi 3-D rendering of the surveyed area. Targets with great conductivity contrast (metallic targets, such as wire mesh, rebar and post tensioning cables) can be located and identified with relative ease (Figure 2). While less conductive targets, such as air voids, honeycombing and delamination can be obscured by reflections emanating from rebar. Detection of such targets, especially if they are deep in a slab or are overlain by two or more layers of reinforcement, cannot always be guaranteed. Good survey procedures and advanced data processing are paramount for the success of such projects.

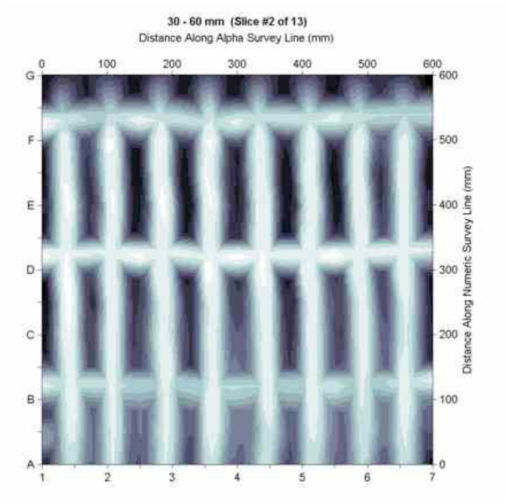

Figure 2. GPR depth slice (C-Scan) showing rebar mesh on the bridge girder from (Figure 1). Bar location and spacing can be directly obtained from the screen display.

Three dimensional displays are fundamentally block views of GPR traces that are recorded at different positions on the surface. Data are usually recorded on a predetermined orthogonal grid where the accurate location of each trace is critical to producing accurate 3D displays. Normally, 3D block views are constructed, then they may be viewed in a variety of ways, including as a solid block or as block slices [5].

Recent advancements in both 3D GPR data acquisition and processing software have allowed high resolution concrete survey data to evolve into a highly effective analysis tool [3].

CASE STUDIES

Since the experience of the author is that most engineers and their clients' still view GPR as “part art, part science” [4] four case studies will be presented with the intention of dispelling the “art” part of GPR data interpretation. These case studies are from the author's consulting practice and show different data sets from simple to complex with the intention of the data speaking for themselves. Accuracy and practical limitations are discussed in each case.

Rebar

Since radar reflections are created by an abrupt change in the electrical and magnetic properties of the material the electromagnetic waves are traveling through, GPR is an ideal tool to detect reinforcing bars in concrete (Figure 2). A 1 GHz centre frequency radar can penetrate over 18 in (45 cm) thick concrete and map the location and depth of rebar mats [2]. With carefully controlled data collection the centre of the bar can be mapped with 100% accuracy. Depth precision depends on antenna frequency, the ability to ground truth the data, depth of targets, and experience of the operator and is generally in the 5% to 25% accuracy range. Radar can distinguish between a wire mesh and rebar, however, the diameter of the bar can only be estimated.

Operational limitations arise when physical access is limited to the survey area or when the density and overlap of rebar significantly attenuate the signal or when bar spacing is below the radar detection limit (Table 1).

Table 1: Horizontal resolution of high frequency GPR antennas in concrete (wave velocity = 0.1 m/ns)

Depth (in)	Depth (cm)	Horizontal resolution (cm)		
		500 MHz	1000 MHz	1500 MHz
2	5	7.1	5.0	4.1
4	10	10.0	7.0	5.8
6	15	12.2	8.6	7.1
8	20	14.1	10.0	8.2
10	25	15.8	11.2	9.1
12	30	17.3	12.2	10.0
14	35	18.7	13.3	10.8
16	40	20.0	14.3	11.5
18	45	21.2	15.1	12.2

Post-tension cables

Post-tensioning is a method of strengthening concrete using high-strength steel strands or cables, in order to build thinner slabs which can cut down on construction

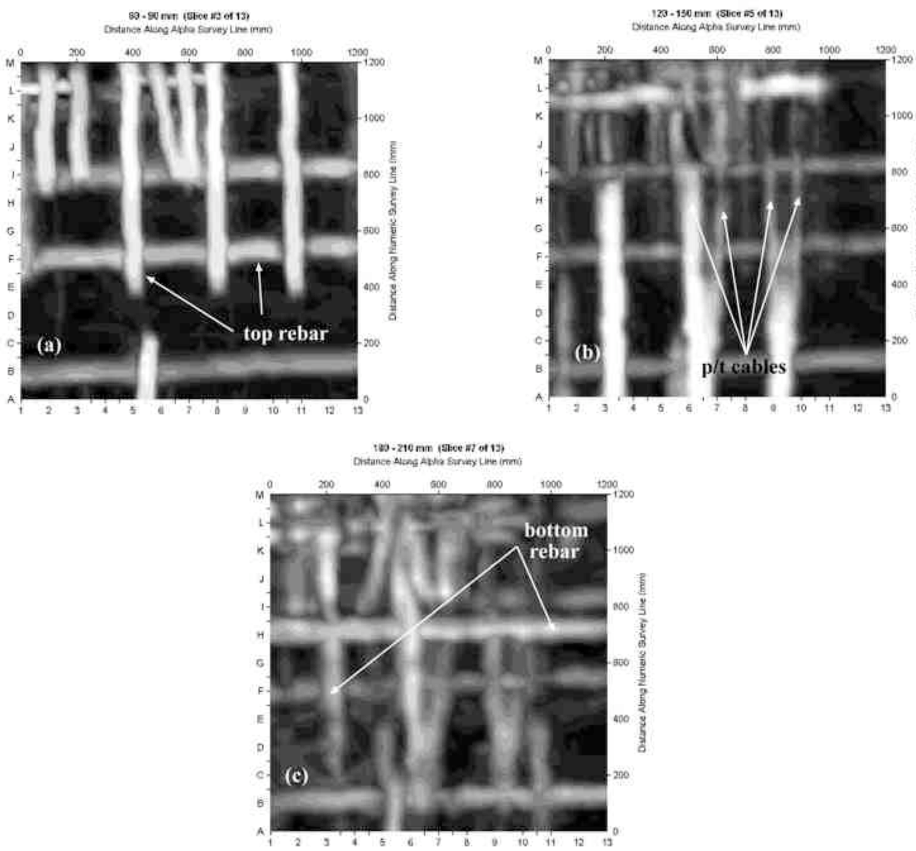

Figure 3. Selected GPR depth slices showing (a) top rebar mesh at 60-90 mm depth, (b) P/T strands at 120-150 mm depth, and (c) bottom rebar at 180-210 mm depth.

costs and curing time. Locating the exact position and depth of these cables is paramount prior to coring, drilling, or trenching into post tensioned slabs.

Similar to GPR detection of rebar, the location of P/T cables in concrete is straightforward. However, since their electrical properties do not differ significantly from those of rebar radar does not identify these targets as P/T cables. An experienced operator, however, can conclusively identify P/T tendons in most situations through carefully controlled data collection (high resolution large grids) and advanced data processing. Selected depth slices show top rebar (Figure 3a), the P/T layer (Figure 3b), and bottom rebar (Figure 3c).

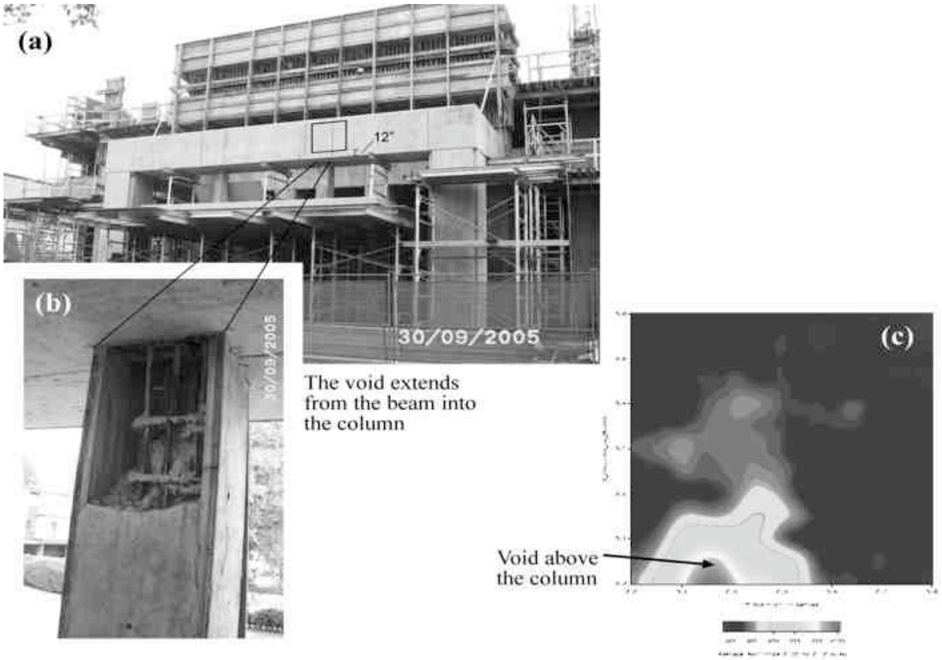

Figure 4. Location photo showing (a) beam under investigation with GPR grid location, (b) column with deficiencies, and (c) processed GPR depth plot showing high amplitude anomaly interpreted as void.

Voids

Detecting voids in or under a concrete slab depends on the size of the void, the spacing and density of the reinforcement, and on the luck of the operator. In other words it can be problematic. The strong, high amplitude reflection emanating from rebar often masks the weaker signals returning from voids.

In our third case study concrete pouring deficiencies became apparent after removal of the formwork on a new high rise construction site (Figure 4a), prompting an investigation of the beam above the deficient column (Figure 4b). Since the beam was heavily reinforced and the existence, size, and location of the void was not known, this task seemed to be a challenge for a 1000 MHz system, since only a small grid (60 cm x 60 cm) could be placed on the face of the beam. The field data viewed on the digital video logger (DVL) did not reveal any anomalies. However, advanced data processing revealed a high amplitude anomaly at 0.4 to 0.5 m depth (Figure 4c).

Fibre reinforced polymers

The term fibre reinforced polymer (FRP) describes a group of materials composed of synthetic or organic fibers embedded in a resin matrix (polymer). The most common FRP's targeted to the construction industry are glass FRP (GFRP), carbon FRP (CFRP), and aramid FRP (AFRP) [7]. The main advantages of FRP materials over conventional steel include no corrosion even in harsh chemical environments and the fact that their density is 20%-25% of that of steel [7]. A number of bridges have been built with FRP bars [7, 8], however, the question of how to locate these bars has not been addressed.

Two test blocks one with GFRP and one with CFRP bars were poured and tested with two high frequency GPR units in order to determine whether GPR can locate the FRP bars. The test slabs were poured in the Materials Laboratory at the University of British Columbia (UBC). Line scan data conclusively confirmed GPR's ability to locate both CFRP and GFRP bars (Figure 5).

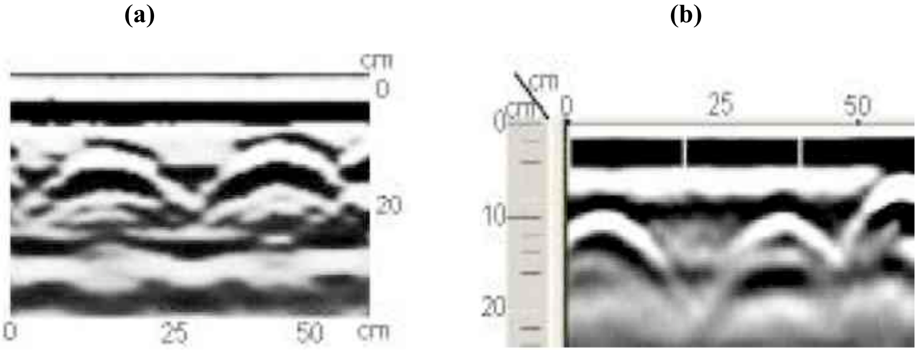

Figure 5. (a) The two hyperbolae represent CFRP bars embedded in concrete. Data were collected with a 1 GHz Conquest system from Sensors and Software Inc. (b) The two hyperbolae represent GFRP bars embedded in concrete. Data were collected with a 1.6 GHz frequency GSSI system.

SUMMARY AND CONCLUSIONS

GPR has become a routine survey tool in the hands of the expert operator for the location of embedded elements such as rebar, post-tension cables, and conduits. The key advantages of radar are the ability to scan large areas quickly and efficiently locate embedded element in a cost-effective manner. Mapping voids inside or under concrete slabs is location specific and requires familiarity with GPR principles and the use of sophisticated processing programs. Mapping delamination and surveying entire parking garages and/or bridge decks is feasible with current technology. To draw conclusive results radar data has to be complemented with half-cell potential readings and destructive testing.

GPR can efficiently map FRP bars embedded in concrete test blocks, therefore, it is a suitable tool for locating FRP bars on bridge decks.

Current research indicates that GPR can measure and map rebar corrosion in bridge decks [9]. The commercialization of this application is currently being developed with pilot studies being scheduled for early 2008.

Due to the key advantages, including safety, the ability to scan large areas quickly and cost-effectively together with only one sided access, real time results, and digital data storage, GPR technology is expected to play an ever increasing role in structural evaluations and infrastructure monitoring, with new technical developments pushing the capabilities of the technology even further.

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