Case Studies and Innovative Uses of GPR for Pavement Engineering Applications

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ABSTRACT

Over the past few decades, advances in technology has allowed electronics and computers in general to become more portable and to be able to store more data than ever before. Ground Penetrating Radar (GPR) is a non-destructive technology that is typically associated with archaeological studies, but has recently become more prevalent in civil engineering field with applications ranging from subsurface utility detection to structural concrete assessments.

The principle of GPR technology is based on the reflection/transmission of microwave electromagnetic energy and recording its response to different materials, which are governed by two physical properties of the material; electrical conductivity and dielectric constant. For reflections to occur at different material interfaces, there must be a contrast in dielectric value (reflection produced at a boundary where the dielectric value changes). During subsurface material/void detection, depending on the size of the target, there will generally be a distinct reflection due to the contrast in dielectric between the subsurface materials and the target structure.

Generally, GPR data is collected using two types of systems: air-coupled and ground-coupled systems. Air-coupled systems are typically vehicle mounted and use an antenna frequency between 1.0 to 2.0 GHz which is capable of a depth of penetration ranging from 0.75 m to 0.9 m below the ground surface. There are a large variety of ground-coupled systems, but typically are mounted using a cart with single, or multiple wheels depending on the size of the antenna and must have constant contact with the surface being scanned. Antenna frequencies range from 16 to 2,600 MHz with depth of penetration ranging from 0.3 m to 50 m.

This paper presents several case studies using both air-coupled and ground-coupled GPR systems in pavement engineering applications ranging from void detection, Species at Risk (SAR) investigations, subsurface utility/structure detection and concrete reinforcement detection.

The results of the case studies show that GPR is a non-destructive data collection method that can be used in several different ways to collect a large amount of data over a large area relatively quickly compared to typical investigation methods (coring or drilling). It is important to understand the limitations of the equipment (signal penetration, size of target, etc.), as well as the appropriate system to use in a specific situation (air-coupled vs. ground-coupled). Ground truth data was also critical in the data analysis and interpretation of the GPR scans. Additionally, using the utility survey cart-mounted antenna in a cross-polarized orientation aided in capturing data in a steel congested structural element and allowed the GPR engineers to help identify voids.

Introduction

Over the past few decades there has been considerable advancement in technology which has allowed computers and electronics in general to become more portable and to be able to store more data than ever before. Ground Penetrating Radar (GPR) is most synonymous with archaeological investigations, however it has become more prevalent in civil engineering applications as the technology has been developed for specific applications including the location of buried utilities and infrastructure, structural concrete assessments (bridge decks, piers, slabs and columns), as well as roadway surveys (pavement layer profiles, sinkholes/voids and frost tapers).

This paper will present several case studies using both air-coupled and ground-coupled GPR systems in pavement engineering applications ranging from void detection, Species at Risk (SAR) investigations, subsurface utility/structure detection and concrete reinforcement detection. The purpose of this paper is to highlight the flexibility of GPR technology and summarize the results and benefits of non-destructive testing utilizing atypical project examples.

Background

This section will provide a brief background on the theory of GPR technology, GPR data collection systems and typical uses for each type of system.

How Does GPR Work?

A GPR system typically consists of an antenna which contains both a transmitter and a receiver. The antenna emits pulses of microwave EM energy at a specific frequency range (typically between 16 MHz to 2,000 MHz) which is dependent on the type of antenna used. During emission of the EM pulses, the antenna receives reflections of the signal when there is an abrupt change in material dielectric permittivity below the surface (Conyers 2013). Essentially, some of the emitted energy pulses are reflected back to the antenna at subsurface features which could include pipes, rocks, void spaces, and soil strata. The travel time of the pulses emitted from the antenna are recorded by the GPR equipment which can then be imported into software which digitizes the reflections and allows the user to determine the depth of the reflection (ie. material interface). The general principle of GPR data collection is illustrated below in Figure 1 using an air-coupled data collection example from a typical roadway application.

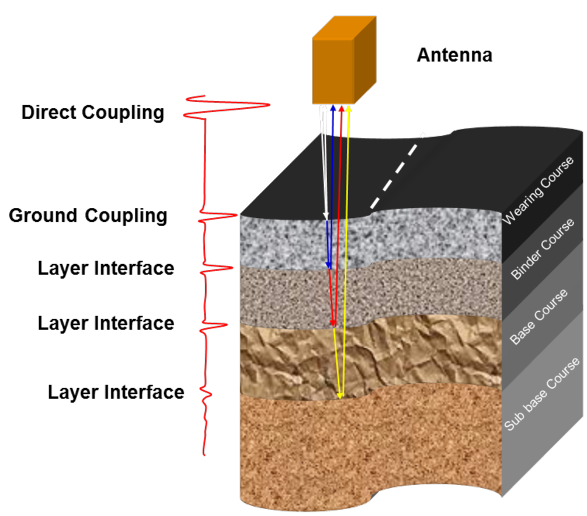

Figure 1: Principle of GPR Data Collection

The quality of the digitized reflections, or resolution, as well as the depth of signal penetration below the surface depend on the frequency of the emitted pulses which are attributed to certain models of antennae. Antennae which operate at lower frequencies (200 MHz to 400 MHz) can penetrate deeper into the subsurface (4.0 m to 9.0 m), however the resolution of the digitized reflections are much lower than the antennae operating between 1,000 and 2,000 MHz due to the higher amplitude of the emitted waves. The differences in the signal amplitude of various antennae are illustrated in Figure 2 below.

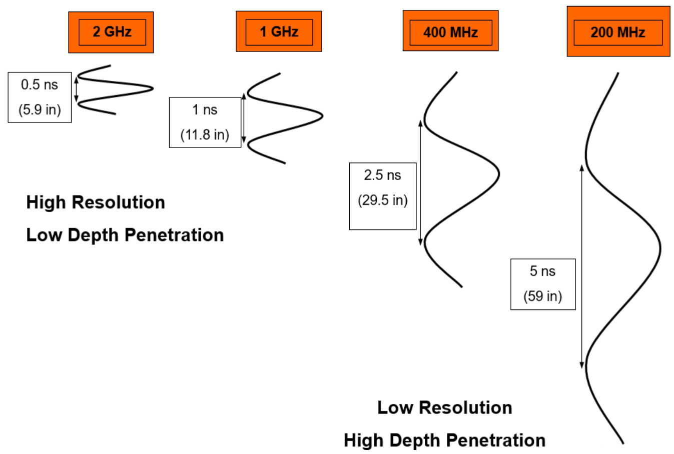

Figure 2: Relationship Between Penetration Depth and Frequency

GPR Data Processing

It is important to note that several factors, such as moisture and soil type, can influence signal penetration and the quality of collected GPR data. GPR signal travels through granulars, sands, glacial tills, and silty soils quite well, however some clay soil types hinder the signal (Saaranketo 1999). The penetration depth in clayey soils depends on the mineralogy and clay content of the subgrade soils. The theoretical penetration depth of a 400 MHz antenna is 4.0 m, however experience in parts of southern Ontario show that the signal can be limited to depths between 1.0 and 1.5 m below the surface irrespective of antenna frequency.

High frequency radio interference caused by overhead wires, cell phone towers, transmission lines, etc. can cause significant “noise” within a data file making it difficult to interpret. This problem is hard to avoid or prevent as these items are typically “fixed” and cannot be “removed” from the vicinity of the test section.

GPR data is processed using data reduction software with RADAN (developed by GSSI) a common package used un North America. The data is processed by identifying reflections caused by changes in the electrical properties (dielectric, electrical conductivity, etc.) of a material. The reflections are digitized and the RADAN software converts the digitized reflections into layer or object depths. Once the layer or object has been identified, the data can be exported, and then summarized and formatted as required.

It is recommended that processed GPR data be calibrated with ground truth information obtained from boreholes or other data (construction history, test pits, etc.). The calibration process involves inputting a known layer thickness at a given point along the GPR survey, into the RADAN software to allow it to calculate the electrical properties for the specific pavement material present on site. By default, the RADAN software will use an assumed average value for the electrical properties of the layer materials if no ground truth information is available. The accuracy of GPR data calibrated with coring information is expected to be within a range of 1% to 10% of the actual pavement thickness, while un-calibrated the accuracy can vary up to 100% (Willett 2002).

GPR Data Collection Systems

Generally, GPR data is collected using two types of systems: air-coupled and ground-coupled systems. Air-coupled systems are typically vehicle mounted (approx. 0.5 m above the surface) and use an antenna frequency between 1.0 to 2.0 GHz which is capable of a depth of penetration ranging from 0.75 m to 0.9 m below the ground surface. A vehicle mounted system manufactured by Geophysical Survey Systems Inc. (GSSI) is shown in Figure 3 below. The antenna can either be mounted at the rear or front of the data collection vehicle. The data is typically collected at the posted speed limit (50 km/h to 100 km/h) with the test pass located in the midlane or wheel path of the lane being surveyed.

Figure 3: Air-coupled GPR System (2.0 GHz antenna)

There are a large variety of ground-coupled systems, but typically are mounted using a cart with single, or multiple wheels depending on the size of the antenna and must have constant contact with the surface being scanned. Antenna frequencies range from 16 to 2,600 MHz with depth of penetration ranging from 0.3 m to 50 m. A three-wheeled cart mounted system manufactured by Geophysical Survey Systems Inc. (GSSI) is shown in Figure 4 below. The cart mounted system is more mobile than the vehicle mounted system, however may require traffic control on or near roadways. Data collection is typically performed at walking speeds (approx. 5 km/h). Some systems have been modified to be able to be pushed or pulled by a vehicle (Saaranketo 1999), however data collection speeds are still limited (between 5 to 15 km/h) to avoid damage to the antenna since constant contact with the ground surface is required (Vilbig 2013).

Figure 4: Ground-Couple GPR System (400 MHz antenna)

Case Study: Ground-Coupled GPR Surveys of Concrete Slabs and Buried Infrastructure

This section will present the data collection methodology and results from two projects where GPR technology was used to survey concrete slabs, buried infrastructure, and other structural elements.

GPR Survey of Structural Building Elements

A comprehensive GPR survey was performed on several structural building elements including structural concrete columns, beams and floor slabs in attempt to identify voids related to issues during construction of these elements. Numerous large voids were observed following removal of the concrete forms and GPR was chosen to perform a comprehensive non-destructive screening of concrete structural elements where a poor-quality mix was used. Sample photos illustrating the extent of the voids is shown in Figure 5 below.

Figure 5: Voids in Concrete Columns

The GPR survey was conducted using a Geophysical Survey Systems Inc. (GSSI) SIR-4000 data acquisition system with a 1,600 MHz general purpose concrete antenna (0.5 m penetration depth) and utility survey cart. This ground-coupled antenna was chosen due to its portability, which is similar in size to a household iron, and the need for high resolution data near the surface being scanned.

Numerous horizontal and vertical and vertical scans were completed on each structural element to obtain complete coverage. As shown in Figure 5 above, the concrete structural elements contained a large quantity of steel reinforcement. Because steel reinforcement is a complete reflector of radar energy, it was difficult to distinguish between a potential void and reflections caused by the congested reinforcement. Data collection was completed using two antenna orientations, conventional orientation, and cross-polarized orientation (turning the antenna 90 degrees). When using the cross-polarized orientation, the antenna is not as sensitive to metallic targets perpendicular to the direction of travel. As a result, this aided in identifying voids located below the reinforcement. Additionally, collecting data using both antenna orientations allowed the reviewer to compare the survey image which aided in void identification. If a potential void was observed during field collection, additional scans were generally collected. For the concrete slab, a grid pattern was laid out along the top surface with grid lines running longitudinally and transversely. Prior to marking out the gridlines, the GPR was used to locate the reinforcement in both directions. The gridlines were then marked out to run the scans between the reinforcement and minimize interference with the GPR signal.

Following processing of the data, a total of 65 void locations were identified (6 locations in concrete slab, 7 in the concrete beams and 52 in the concrete columns). A sample screen capture of a void in a concrete slab is shown in Figure 6 below.

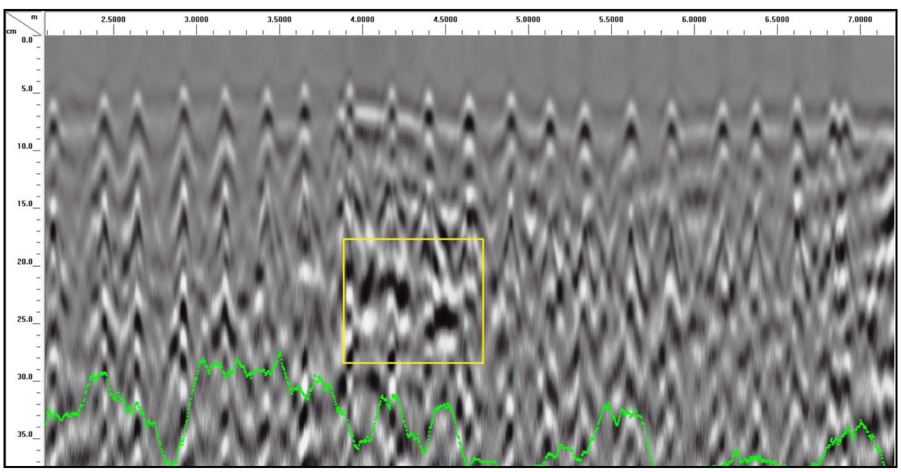

Figure 6: Void in Concrete Slab

GPR Survey of Concrete Slab

This project example will detail the data collection methodology and results from a forensic investigation of a failed concrete slab. The investigation included a condition assessment, geotechnical coring, boring and sampling of subsurface soils for materials characterization as well as ground-coupled GPR to explore the subsurface support conditions (ie. voids, buried infrastructure, etc.). For the purposes of this paper, only the GPR data will be presented.

The concrete slab experienced premature cracking distresses shortly after construction. A 400 MHz ground-coupled antenna was selected for this investigation due to its capability of collecting data up to 4.0 m below the surface. The subgrade was known to be composed of glacial till materials based on previous investigations, so good GPR signal penetration was expected. The slab layout is illustrated below in Figure 7.

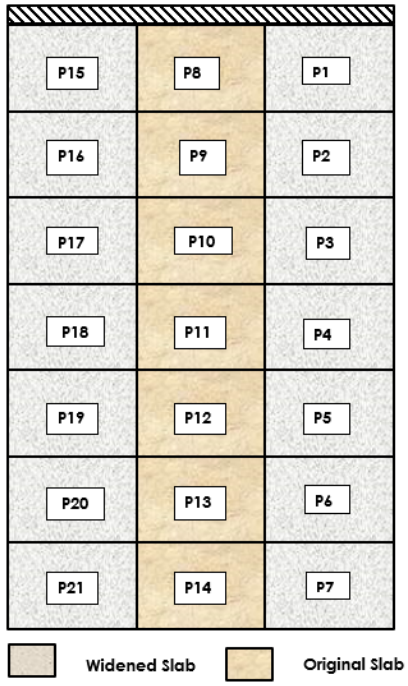

Figure 7: Concrete Slab Layout

The survey was conducted using multiple longitudinal and transverse passes with an approximate 0.3 m spacing between passes. During data collection, the GPR operator noted that the slab reinforcement differed between adjacent slabs. A sample screen capture from the raw GPR data is provided below in Figure 8. The GPR scan in Figure 8 was completed from Slab P1 to Slab P15, in the transverse direction, and it is apparent that the original slab (Slab P8) contains a steel mesh reinforcement, while the widened slabs (Slabs P1/P15) contain steel tie bars which indicates that the widened slabs were attached to the foundation of the adjacent building. Tie bars in the original slab were not observed in the GPR scans, thus indicating the original slab was isolated from the building foundation.

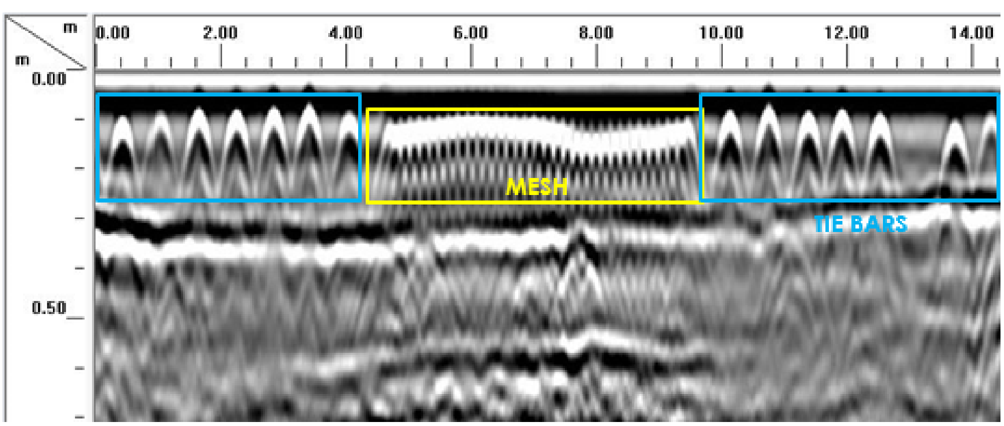

Figure 8: Concrete Slab Reinforcement Variation

The condition survey completed at the time of the investigation noted cracking propagating from the locations where the tie bars were connected to the foundation of the building. It is reasonable to postulate that the cracking was a result of differential movement between the slabs as a result of the joint details caused premature cracking in the slabs at the slab/foundation interface.

GPR Survey of Buried Infrastructure

A ground-coupled GPR survey was conducted on an old abandoned industrial property with the objective of determining if any remnants of old structures were buried following their decommissioning. Prior to completing the field investigation, historical records for the property showed that it had undergone numerous expansions over the past 100 years and typically supplanted old residential properties. The 400 MHz ground-coupled antenna was chosen for the purposes of locating the remnants of buried structures. The ground-coupled cart system was paired with a Trimble Global Position System (GPS) for the purposes of this project to enable the mapping of any utilities or buried infrastructure.

To collect GPR data at the required depth, the antenna was set to collect at 54.4 nanoseconds, or up to a depth of approximately 3.0 m below ground surface. Data was collected at a scan rate of 50 scans per metre. The entire project site was roughly 27 acres, however the areas designated for the GPR survey was much smaller (approx. 7 acres). A total of 100 GPR files were collected using a grid pattern with an offset of approx. 5 m between adjacent passes.

The data was processed using RADAN and exported to a Keyhole Markup Language (KML) file capable of being plotted using Google Earth. By comparing the processed data plotted in Google Earth to historical property drawings, the remnants of old structures could be identified. Steel reinforcement, from an old floor slab, was detected and compared to the historical drawings (shown in Figure 9). GPR layer anomalies, interpreted to be debris from an old building, were flagged during data processing and compared to the historical drawings (shown in Figure 10). The extent (area) and depth to the buried infrastructure was provided land development teams to consider in the design of their site layout.

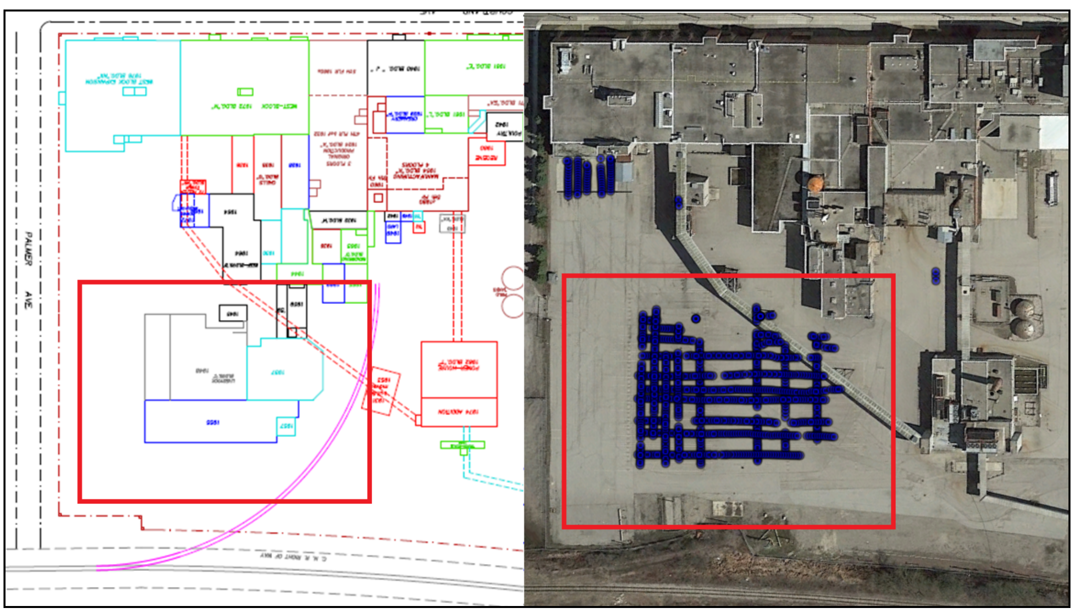

Figure 9: Old Building Floor Slab - Steel Reinforcement

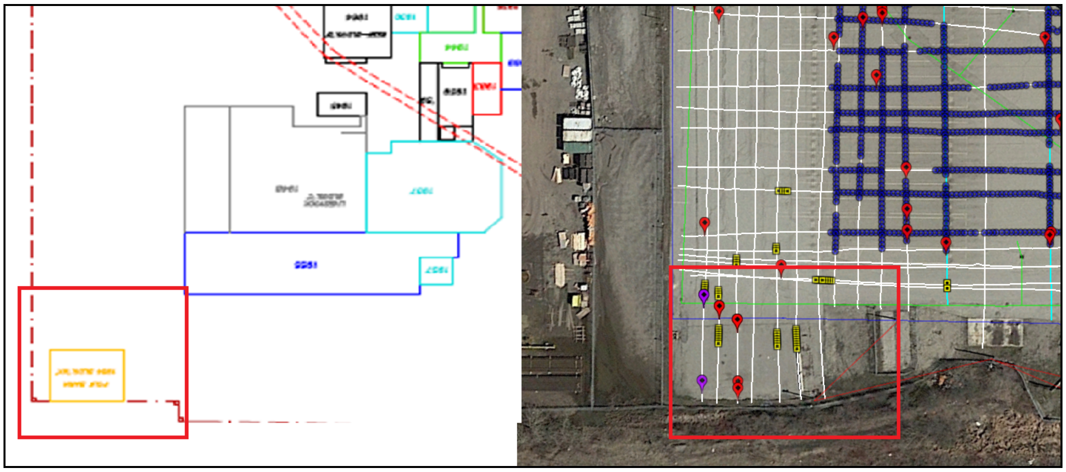

Figure 10: Buried Debris from Old Building

The GPR data collected from the survey was used to determine excavation quantities and design layout alternatives based on the location of the buried infrastructure on the project site as well as the proximity to the surface.

Case Study: GPR Surveys for Species at Risk (SAR)

Turtles nest in areas with sand and gravel and other loose substrates, with suitable sunlight and good drainage, including roadsides, and other disturbed areas. The presence of nests may pose constraints to construction and operation of roads and other engineering projects in Ontario (Clancy 2011).

Throughout Ontario, turtles have been observed to nest in the embankments and gravel shoulders of roadways located near wetlands. The ease of access to these nests enables the use of non-destructive technologies, such as ground penetrating radar (GPR), that are capable of locating these nests relatively quickly. The turtle nests are essentially void spaces in the gravel shoulder and can be detected using GPR because of the change in the reflected radar signal velocity.

Turtle nesting sites are difficult to identify in the field using conventional practices, which involve using a qualified biologist to perform a visual survey and inspect the potential nesting sites. The turtle nests themselves are generally flask-shaped, with the narrowest part at the top and the eggs down below in a wider chamber. The nests are buried below the surface at an unknown depth and are surrounded by gravel, sand and silt materials. The opening at the top of the nest is smaller in diameter than the width of a work boot.

Since turtles are known to return to the general location of the nesting site each year, a GPR survey was conducted to determine the extent of the nesting locations. The areas designated for the survey were located near wetlands and known historically to be a prevalent nesting location. The survey was completed using a ground-coupled 400 MHz antenna, paired with a Trimble GPS, in the gravel shoulders with an offset of 0.3 m between adjacent passes. The layout of the GPR survey plan is provided below in Figure 11. Additionally, the survey was completed in a window between nesting and hatching of the turtle eggs.

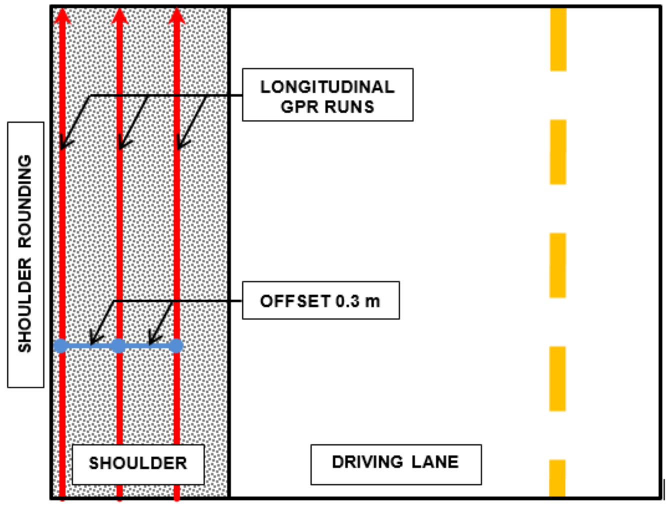

Figure 11: GPR Survey Plan

Ground truth information was essential for this project as the turtle nests are relatively small in area and could be mistaken for buried debris or signal interference. GPS data was obtained from a previous investigation performed by a qualified biologist from the beginning of the nesting season. The known nesting location was located at the beginning of the investigation by field technicians using a handheld GPS system and subsequently surveyed with multiple passes of the GPR. This data would be used during post-processing to ground-truth and calibrate all the GPR data files collected along the roadway. A sample of the GPR scan of the calibration nest is shown in Figure 12 below.

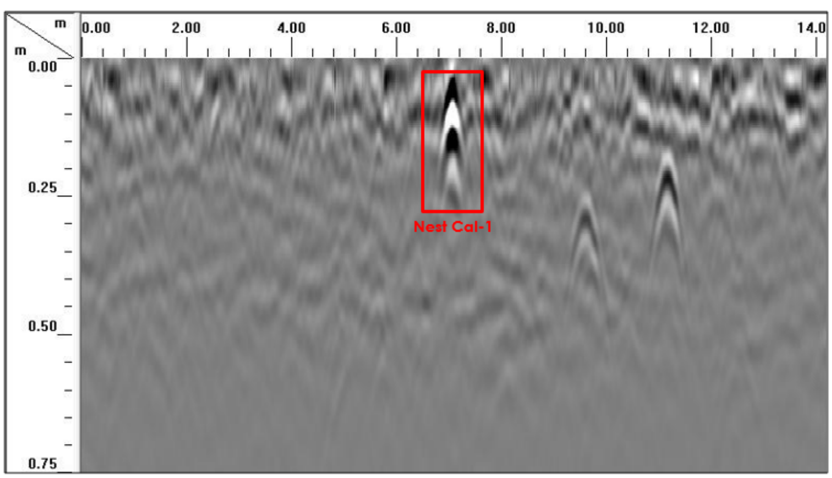

Figure 12: Ground Truthed Nesting Location

The processed data was exported into a KML file and plotted in Google Earth along with the depth to the top of the nesting chamber. A sample of the plotted results are provided in Figure 13 below.

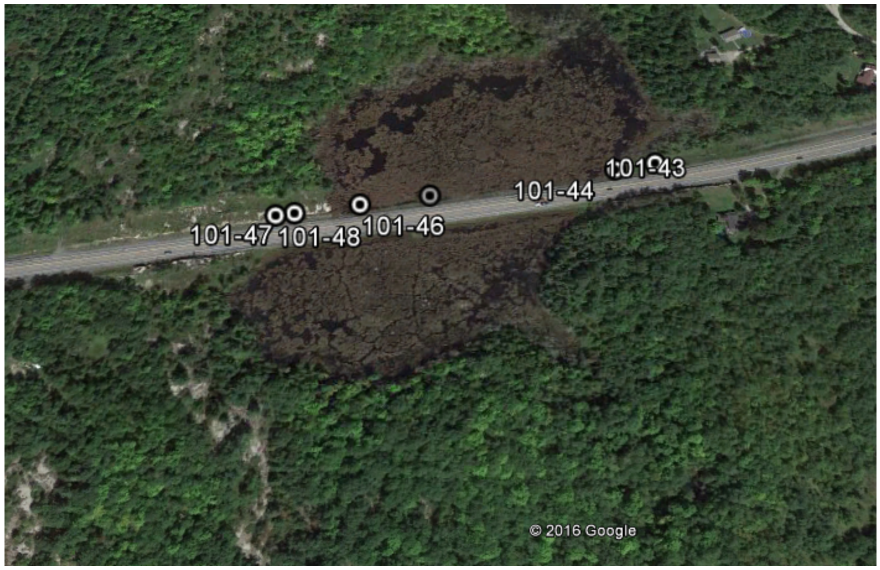

Figure 13: Turtle Nesting Sites

One major issue identified during the case-study of this project which requires further research and examination is; how can we be certain that the identified nest locations are active and the eggs are still present and have not been affected by predation? More ground-truth information is required to discern an old or predated nest and an active one.

Case Study: Comparison of Air-Coupled and Ground-Coupled GPR Surveys for Buried Infrastructure

This section of the paper will focus on project examples using air-coupled GPR surveys to locate buried infrastructure and comparing to results of using a ground-coupled unit for the same purpose.

A section of road in Southeastern Ontario was surveyed using a vehicle mounted 1.0 GHz air-coupled GPR unit to locate buried abandoned culverts. The approximate location of the abandoned culverts were determined from historical contract documents. The approximate depth of cover from historical records was noted to be approximately 1.5 m below the pavement surface. To collect high resolution GPR data, the antenna was set to collect at 20 nanoseconds. Data was collected at a scan rate of 4 scans per metre.

The cart mounted GPR surveys were completed using ground-coupled 270 and 400 MHz antennae. The ground coupled antennas were set to collect at 70 to 97 nanoseconds, or up to a depth of approximately 2.5 m to 3.5 m below ground surface for the 400 MHz and 270 MHz antennas respectively. The scan rate was set to 50 scans per metre.

Consecutive longitudinal passes using each set of equipment was performed. The vehicle mounted survey was only completed in the midlane and outer wheelpath due to antenna positioning constraints with a vehicle mounted system. Longitudinal passes were completed with 0.3 m offsets between adjacent passes. The passes were completed approximately 30 m on either side of the estimated historical culvert locations.

The ground-coupled data was completed in two separate field visits using two different GPR antennae (270 MHz and 400 MHz antennae). The first ground-coupled GPR survey completed using the 400 MHz antenna, however the penetration of the GPR signal was severely limited and ranged from 1.0 m to 1.5 m below the surface. The theoretical penetration depth listed by the manufacturer for the 400 MHz antenna is specified as 4.0 m. The subgrade soils in the area were known to be composed from clay materials and most likely impeded the emitted signals. In an attempt to test the capabilities of ground-couple antennae in the specific geographic area, a second GPR survey was performed using a 270 MHz antenna which had a specified penetration depth of up to 6.0 m. A comparison of the GPR scans is shown below in Figure 14. The first image was collected using the 270 MHz antenna and the second image was collected using the 400 MHz antenna.

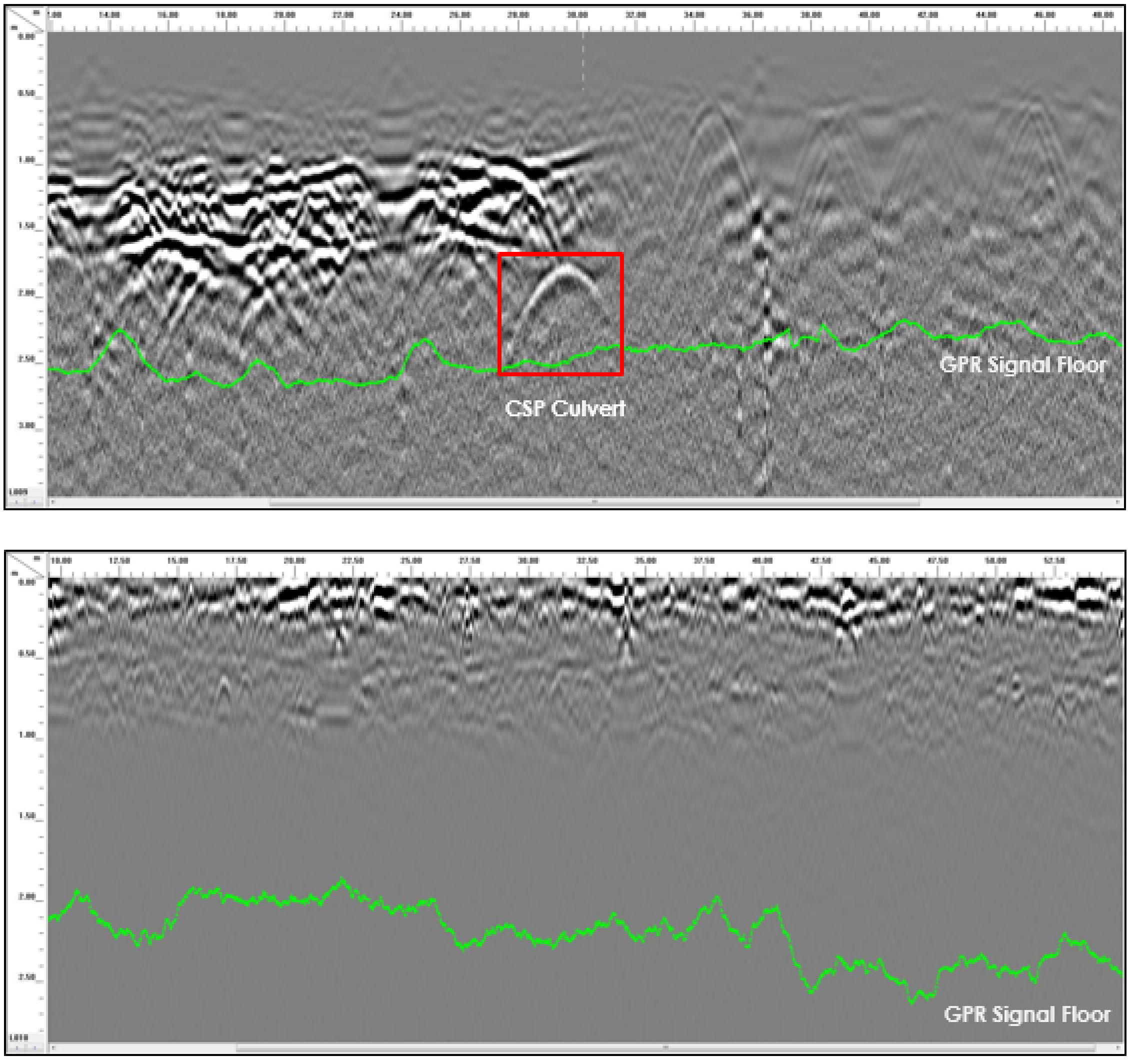

Figure 14: 270/400 MHz Antennae - Data Comparison

The ground-coupled data was completed in two separate field visits using two different GPR antennae (270 MHz and 400 MHz antennae). Although the maximum penetration depth of the 400 MHz antenna is specified as 4.0 m, analysis of the collected GPR data shows that the data was difficult to interpret below 1.2 m in depth. The second GPR survey was completed using a 270 MHz antenna which has a specified maximum penetration depth of 6.0 m. Data collected using the 270 MHz antenna was useable to a depth of approximately 3.0 m below the existing surface.

The 1.0 GHz air-coupled GPR data collected were also analyzed to determine if culverts could be detected with the vehicle mounted antenna. The 1 GHz GPR air-coupled antenna was not able to detect the culvert in Figure 14. It should be mentioned that the air coupled GPR, operating at highway speeds, is limited to 4 scans per metre or 1 scan every 250 mm. As such, there is a higher probability it will miss the smaller culverts, such as the 300 mm CSP culvert. The ground coupled antennae by comparison, have a much higher scan rate of 40 to 50 scans per metre for the 400 MHz and 270 MHz, respectively. Based on these results, it was determined that the 1.0 GHz air-coupled antenna is generally not suitable for locating culverts.

Conclusions

As shown in this paper, GPR is a non-destructive data collection method that can be used in several ways to collect a large amount of data over a large area relatively quickly compared to typical investigation methods (coring or drilling). It is important to understand the limitations of the equipment (signal penetration, size of target, etc.), as well as the appropriate system to use in a specific situation (air-coupled vs. ground-coupled).

Ground-coupled GPR data can be used in investigations with various antennae to locate voids, buried infrastructure and provide information on the location and type of reinforcement in concrete slabs. Additionally, data can be collected with a ground-coupled unit using a cross-polarized orientation where there is significant interference from steel reinforcement.

Vehicle mounted GPR surveys are quick, safe, and efficient in collecting data on roadways, however lack the level of detail needed for buried infrastructure or obtaining scans of steel reinforcement. The major drawback of ground-coupled GPR on roadways is the need for traffic protection, however research is currently ongoing for new data analysis methods using air-coupled GPR data that can provide similar results to the data obtained from ground-coupled systems (Vilbig 2013).

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