Ground Penetrating Radar for Concrete Evaluation Studies

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ABSTRACT

Ground Penetrating Radar (GPR) is a geophysical imaging technique used for subsurface exploration and monitoring. It is widely used within the forensic, engineering, geological, mining and archeological communities. GPR provides an ideal technique for concrete evaluation in that it has the highest resolution of any subsurface imaging, non-invasive method and is far safer than other method such as x-ray technology. Recent improvements in hardware, and in particular, software processing have contributed to the rapidly expanding popularity and usability of this technique.

Concrete evaluation studies utilizing GPR include the inspection of various foundation floor systems such as structurally suspended slabs, post tensioned or conventionally reinforced slab-on-grade foundation systems, retaining walls, decks, tunnels, balconies and garages. Typically, the objectives of these studies are to accurately locate and/or delineate rebar, tension cables, grade beams, conduits, voids and slab thickness. Several case studies will be presented where such objectives have been achieved.

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INTRODUCTION

Ground penetrating radar covers a wide area in a relatively short period of time for concrete evaluation studies. Due to recent hardware and software advances, real time cursory analysis can be performed at the site. Because of these and other reasons, GPR has become an increasingly attractive method for the engineering community, in particular for shallow, high resolution applications such as concrete evaluation studies. Standard test methods and guides involving GPR have been derived by the American Society for Testing and Materials (ASTM). ASTM D 4748-87 is a standard test method for the exploratory use of GPR for the determination of pavement layer(s) thickness. A more recent and broad guide for GPR usage for subsurface investigation is standardized in ASTM D 6432-99. This ASTM guide provides a compendium of related GPR information useful for a wide range of applications including concrete evaluation studies.

GPR is a non-destructive technique that emits a short pulse of electromagnetic energy, which is radiated into the subsurface. When this pulse strikes an interface between layers of materials with different electrical properties, part of the wave reflects back, and the remaining energy continues to the next interface. GPR evaluates the reflection of electromagnetic waves at the interface between two different dielectric materials. The penetration of the waves into the subsurface is a function of the media relative dielectric constants (ε). If a material is dielectrically homogeneous, then the wave reflections will indicate a single thick layer.

Ground penetrating radar directs electromagnetic energy into the subsurface. The propagation of electromagnetic energy is described by Maxwell's equation with the electric component (E) orthogonal to the magnetic component (H) (Reynolds, 1997). For concrete evaluation studies, both components are equally important. Concrete material is a low conductivity, non-metallic medium that is ideal for GPR signal propagation. However, concrete typically has steel reinforcement, which is a metallic and therefore completely reflects the GPR signal and shadows anything directly below the metal. If applicable, the sub-base beneath a concrete unit is non-metallic. The sub-base may be highly conductive soils (such as expansive clays) that effectively attenuate the GPR signal propagation thereby limiting depth penetration. The relative dielectric constant (ε) of non-metallic medium is a function of three different materials within the medium – solid, fluid and gas (Lytton, 1995). Therefore, for example, the relative dielectric constant for an unsaturated soil is a combination of the relative dielectric constant of the air, relative dielectric constant of water, relative dielectric constant of soil, porosity and degree of saturation.

The velocity in which electromagnetic energy propagates through any medium is a function of the relative dielectric property, speed of light ($c = 0.3$ meters/nanosecond) and magnetic permeability (μ). The magnetic permeability is equal to one ($\mu = 1$) in a non-metallic medium and therefore is not a factor for the

wave propagation velocity. Wave propagation velocities (*V*) through a given medium are important to convert a time domain radargram model into a distance domain radargram model.

OPERATION PRINCIPLES

There are several antenna manufacturers, antenna types, signal pre- and post- setting options, operating frequencies, software packages, etc. to consider for a specific application within the engineering and construction industry, geological, environmental and/or archaeological fields. Each radar system must be designed to meet the objective(s) of a given project. For concrete evaluation studies, there are several options available – all of which have certain advantages and disadvantages. For the evaluation of various concrete structures, which include streets/highways, parking lots, bridge decks, pools, tilt wall panels, sidewalks, various foundation systems and retaining walls, a versatile and highly portable radar system with a ground coupled, monostatic antenna is suitable. However, for specialized projects, such as road condition evaluation, an air-launched (horn) antenna is commonly used due to the efficient data collection characteristic of this antenna. Currently, GPR data can be collected with these air-launched antennae at highway speeds.

A typical radar system for concrete evaluation studies generally consists of a control unit (computer), pulse generator, transmitting and receiving antennae and video monitor. A bistatic antenna describes a radar system with two antennae, one to transmit and the other to receive. An antenna that both transmits and receives is defined as a monostatic antenna. There are advantages and disadvantages of each antenna type for a given application; however, for concrete evaluation studies, monostatic antennae are typically more advantageous due to higher data collection and processing efficiency.

For concrete evaluation studies provided in this paper, a Geophysical Survey Systems, Inc. SIR 10B control unit is used with a monostatic antenna operating at a central frequency of 1.5 gigahertz (GHz) to evaluate the subsurface conditions of a particular site. High vertical and horizontal resolution is essential for concrete studies; whereas depth penetration is not. Typically, high frequency antennae greater than 900 megahertz (MHz) are used to collect high resolution data for concrete evaluation studies. In general, the higher the antenna frequency, the higher resolution power, but lower penetration depth. Based upon current 1.5 GHz antenna configuration, signal penetration depths below approximately 1 to 2 feet from the top of the surface are not probable although some deeper penetrations are possible in some materials.

Figure 1 provides the primary components of a radar system used extensively for several concrete evaluation studies. As previously stated, there are numerous system variations and/or alterations which can be used effectively. The control unit

(A) comprises of an electronic data storage unit and pulse generator in one unit. The monostatic 1.5 GHz antenna (B) is encased within a broom-like device (C), which includes a survey wheel essential for horizontal spatial control. The monitor display (D) allows for on-site cursory analysis. A hundred foot cable (E) attaches the antenna to the control unit. A direct current (DC) power conversion unit (F) may also be necessary if the power source originates from a 110-volt alternating current source. More recent radar systems are now available that are more compact for field portability.

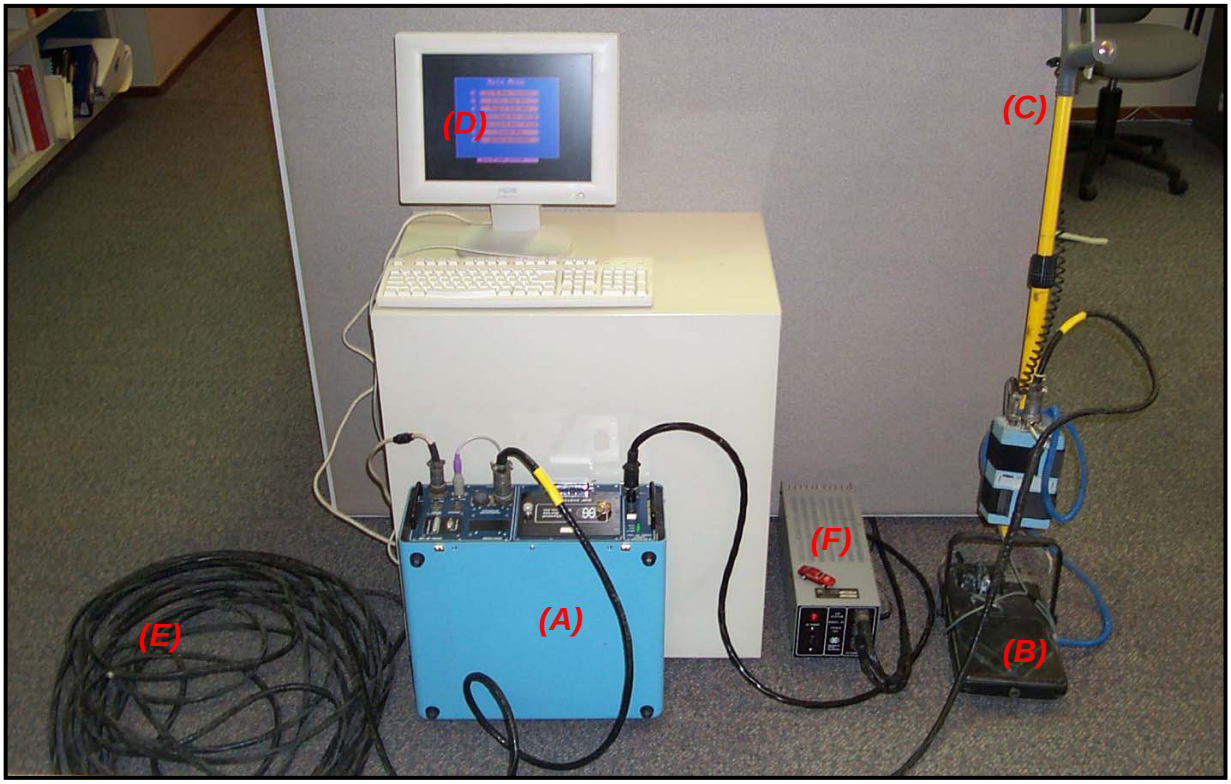


Figure 1 – Ground Penetrating Radar System Components

PROPAGATION WAVE ANALYSIS

Received GPR signatures or wavefronts are basically dependent on the electromagnetic properties of the tested medium or mediums through which the energy passed through. These signatures are important for the identification, qualification and/or quantification of subsurface features. GPR signatures include reflection strength, signal polarity, two-way travel time, signal attenuation and hyperbolic reflection, most of which will be discussed hereafter.

Reflection Strength

Like many other geophysical techniques employed, a material property contrast is necessary for subsurface identification, qualification and/or quantification. For example, seismic surveys, which utilize elastic strain energy, are reliant on contrasting seismic velocities of media. The elastic strain energy for seismic exploration is analogous to electromagnetic energy used for GPR exploration. The velocities at which seismic waves propagate through any given medium are dictated by the elasticity modulus and density. The velocity at which GPR propagates through a medium is a function of the dielectric constant. Changes in moduli and densities result in incident seismic wave reflections. Similarly for GPR, changes of dielectric properties of two materials result in electromagnetic wave reflections. The greater the dielectric contrast between two media, the greater amount of reflected energy. The amount of energy reflected is a function of the dielectric properties of adjacent media. The reflection coefficient (*R*) quantifies the reflective strength between two adjacent media:

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} \tag{1}$$

where ε_1 and ε_2 are the dielectric constants of media (or layers) 1 and 2, respectively. Therefore, the larger the dielectric contrast between two media, the larger the reflection coefficient and subsequently, layer delineation and subsurface feature detection is more evident. Figure 2 plots the reflection coefficient of layer 1 with respect to a range of dielectric constants between 1 and 81. The dielectric constant of layer 1 equals seven, which is typical for a concrete layer. As shown in Figure 2, the larger the dielectric contrast, the stronger the reflection.

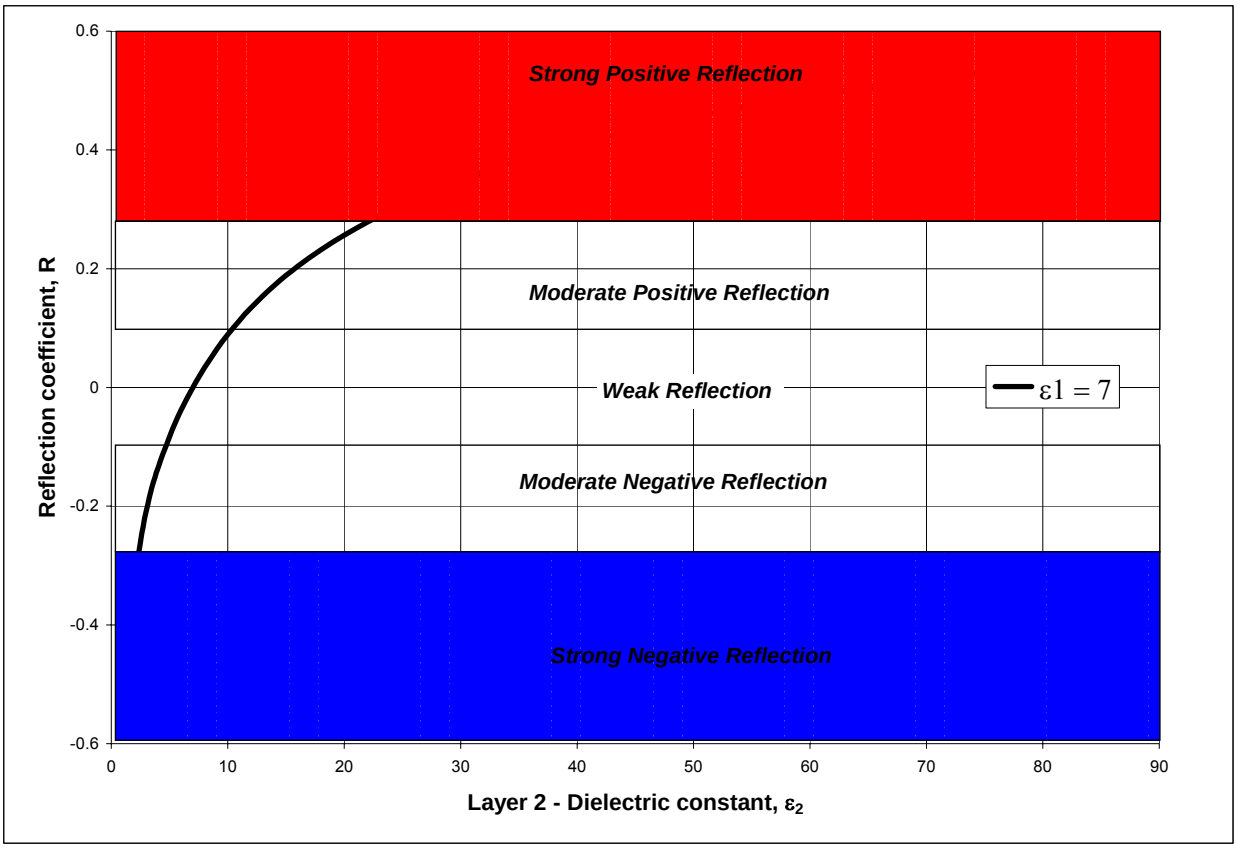


Figure 2 - Reflectivity Chart for Concrete

Assuming a dielectric constant of seven for concrete, if layer 2 has a dielectric between 5 and 10, a weak reflection would occur and layer delineation would be difficult. Therefore, certain site and subsurface conditions are not conducive toward layer delineation due to a lack of dielectric contrast between the two adjacent layers. Figure 3 provides a table of common dielectric constants encountered during concrete evaluation studies. The curve represents the propagation velocity (V) of electromagnetic energy through a given non-metallic medium as represented by the following equation:

$$(2) \qquad V = \frac{c}{\sqrt{\varepsilon}}$$

where c is the speed of light through air (0.3 m/ns). As shown in Figure 3, certain underlying soil conditions such as wetter clay may have similar dielectric constant as concrete, which would result in a weak reflection or no reflection at that interface between the two medium. On the other hand, if an air-filled or water-filled void space is present beneath the concrete slab, a strong wave reflection will occur at this interface. The corresponding reflection coefficient (R) for an air-filled or water-filled void would exceed $\pm$ 0.4 as shown in Figure 2.

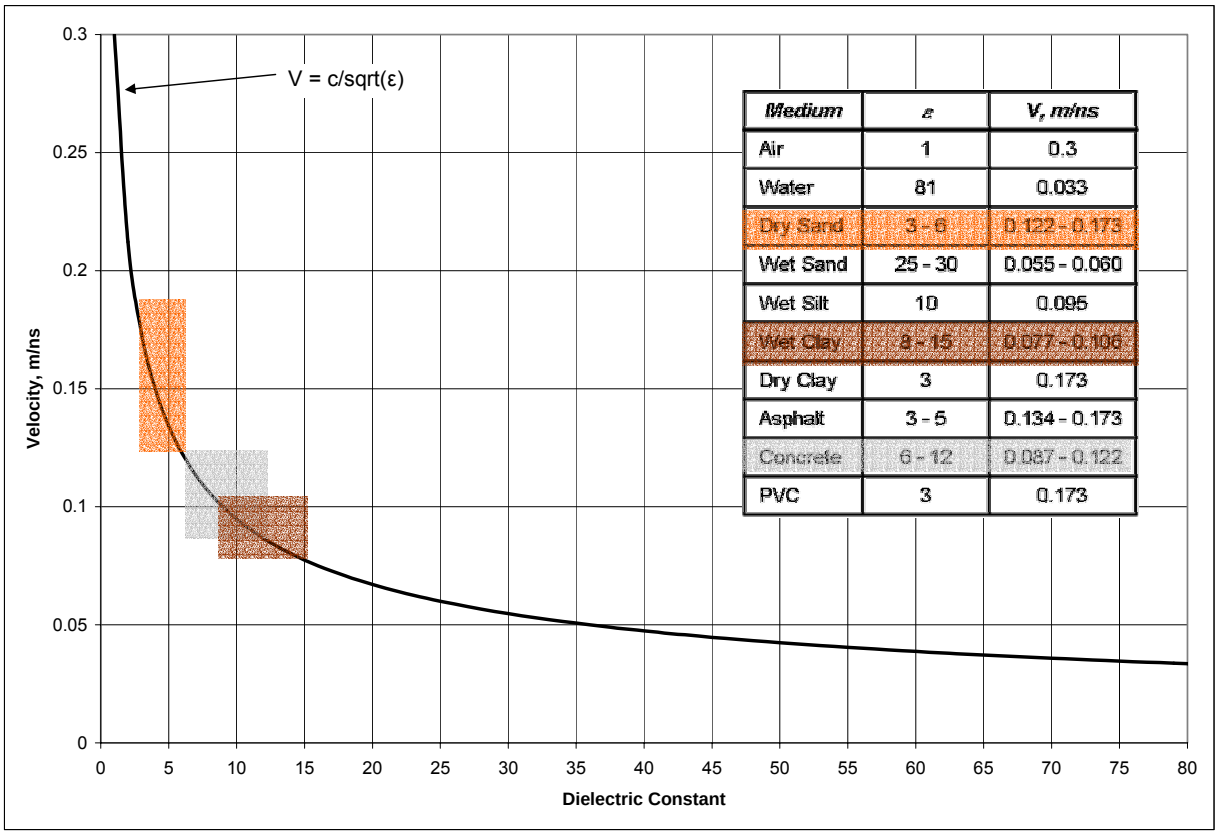
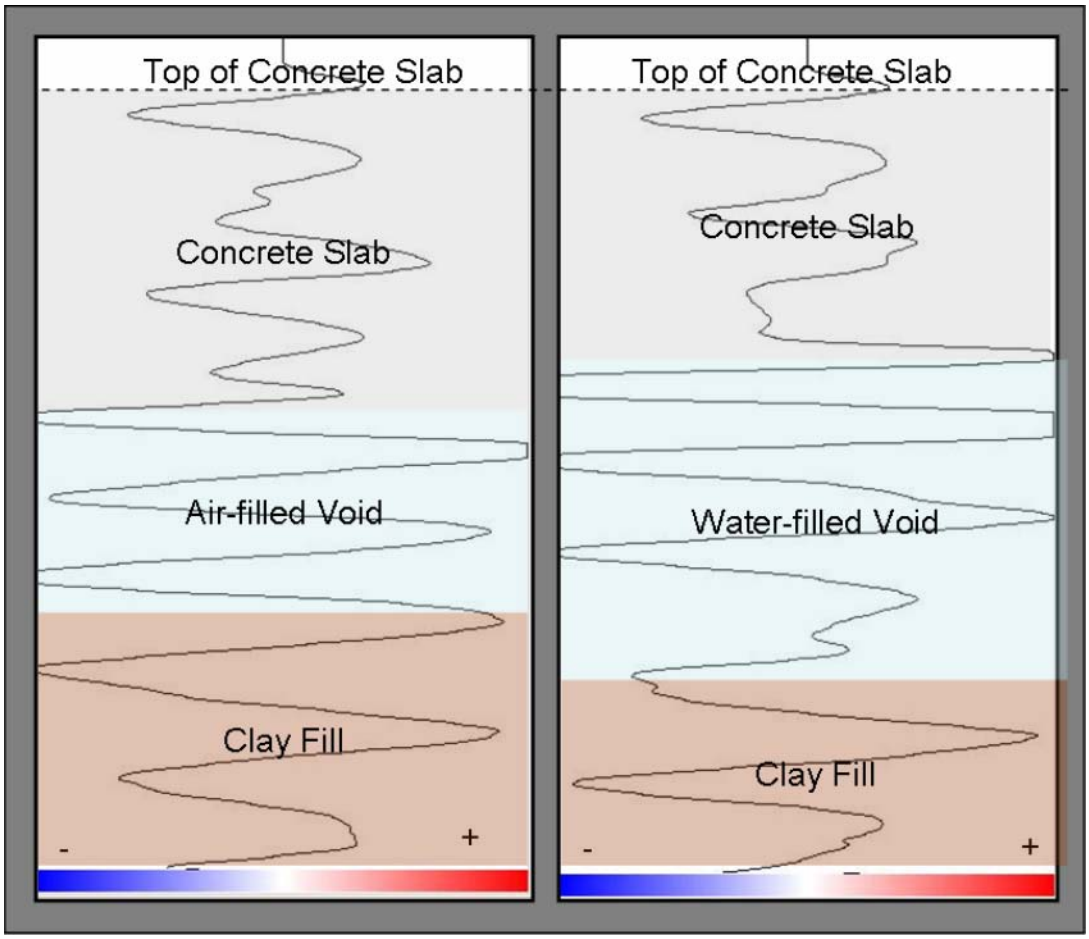


Figure 3 - Dielectric Constants for Concrete Evaluation Studies

Signal Polarity

Reflection polarity can also provide valuable information regarding subsurface conditions beneath the concrete unit. Reflection polarity is also a function of the dielectric constant between two media. If the reflection coefficient, R, is a positive value, a positive amplitude precedes a negative amplitude on the reflection signal. The signature of a reversed polarity is just the opposite - negative amplitude followed by a positive amplitude. Reversed polarity due to phase inversion occurs when the dielectric constant of layer 1 is greater than the dielectric constant of layer 2, which results in a negative reflection coefficient. Figure 2 also indicates the predicted polarity of the received signal based on dielectric variations of layer 2 with respect to layer 1 (concrete). A reversed polarity will occur within the blue shaded region and is typical for an air-filled void beneath a concrete slab unit. The other side of the dielectric spectrum is water (ε = 81) where a positive reflection proceeds the negative reflection. The red region in Figure 2 graphically represents this type of condition.



a. b.

Figure 4 – Oscilloscope Return Signal for (a) air-filled void beneath concrete slab and (b) water-filled void beneath concrete slab.

Figure 4 provides radar signal data performed underneath the structurally suspended foundation slab. As shown in Figure 4b, areas underneath the foundation slab with water-filled void space resulted in a positive amplitude at the concrete slab and void interface. A phase inversion occurred at the concrete and air void interface as indicated by a negative amplitude preceding a positive amplitude. This principle in determining air- or water- filled void space can also be useful for content detection within buried PVC piping. An air-filled PVC pipe will have opposed polarity with respect to a water-filled PVC pipe.

Figure 5 provides a representative radargram of water-filled plastic tubing within a slab-on-grade foundation system. In each of the radargrams provided in this paper, the amplitude of the GPR data is represented by red, blue and white colors. Red colors represent a positive reflection. Blue colors represent a negative reflection. White areas are indicative of minute reflected areas, typically indicative of a dielectric uniformity within a given medium. The blue arrow marks the position of the water-filled tubing. The tubing is represented by a red color (positive reflection)

over a blue color (negative reflection). If this tubing was air-filled, opposite polarity would have been recorded – blue color (negative reflection) over a red color (positive reflection). The plastic tubing was part of a floor heating system that piped warm water underneath the concrete slab.

Two-Way Travel Time

The time it takes for the signal pulse to travel to a certain interface and back to the receiving antenna is referred to the two-way travel time. Variations in two-way travel times within a medium such as concrete suggest the presence of variable concrete thicknesses. A shorter two-way travel time would be indicative of a thinner concrete section. A thicker concrete section would yield a longer two-way travel time. In-situ cursory analyses of two-way travel times are important for grade beam detection in slab-on-grade foundation systems. If grade beam location is pertinent information for the structural evaluation of a slab-on-grade foundation system, a steep increase in two-way travel time would be the pertinent signature within the radargram.

Two-way travel time is also important in the conversion of time domain radargram models into distance domain radargram models. Two-way travel time through a given medium is typically collected at a known depth location (usually by means of coring). The propagation velocity (V) can then be calculated based on the known travel times (tt) and medium depth (d) at particular location based on the simple formula:

$$(3)\ V = \frac{2 \times d}{tt}$$

Equations 2 and 3 can then be used to approximate the relative dielectric constant, ε, for a given medium. This velocity analysis provides the most accurate means to convert radargram from time domain to distance domain. Other methods include the assignment of relative dielectric constants from documented resources such as the table provided in Figure 3, geometric scaling utilizing a data migration technique and common depth point, which is uncommon in concrete evaluation studies.

Hyperbolic Reflection

When the transmitting antenna radiates energy into the subsurface, the radiating beam is conical in nature. The cone angle may range between 60 to 90 degrees with the apex of the cone in the center of the antenna. Due to this broad energy transmission pattern, hyperbolic shapes from reflections occurred when the antenna crosses a linear target (steel reinforcement, pipes) situated perpendicular to the antenna path. The hyperbolic shapes develop because of antenna beam has a broad transmission pattern; therefore, the radar antenna will detect the target not only when it's directly above it, but also before and after the target. As the antenna approaches the target, the left leg of the hyperbola is formed. The apex of the

hyperbola represents the top of the target. As the antenna retreats from the target, the right leg of the hyperbola is formed. The hyperbolic shapes of several targets (rebar) are shown in the time domain radargram section in Figure 5.

The shape of the hyperbola is a function of scan spacing, which a controlled setting within the radar system, and dielectric medium that embeds the target. The higher the relative dielectric constant value, the lower the propagation velocity and more focused (less broad) the conical energy transmission into the ground (Conyers et al. 1997). Therefore, a target embedded within a medium having higher relative dielectric constant will produce thinner hyperbolas and vice versa. Hence, since the shape of the hyperbola is a function of the dielectric medium of which the target is embedded within, propagation velocity, *V*, can be estimated based on geometric scaling techniques. Geometric scaling involves the migration of GPR data from a time domain radargram image to a "real world" distance domain radargram image of the subsurface.

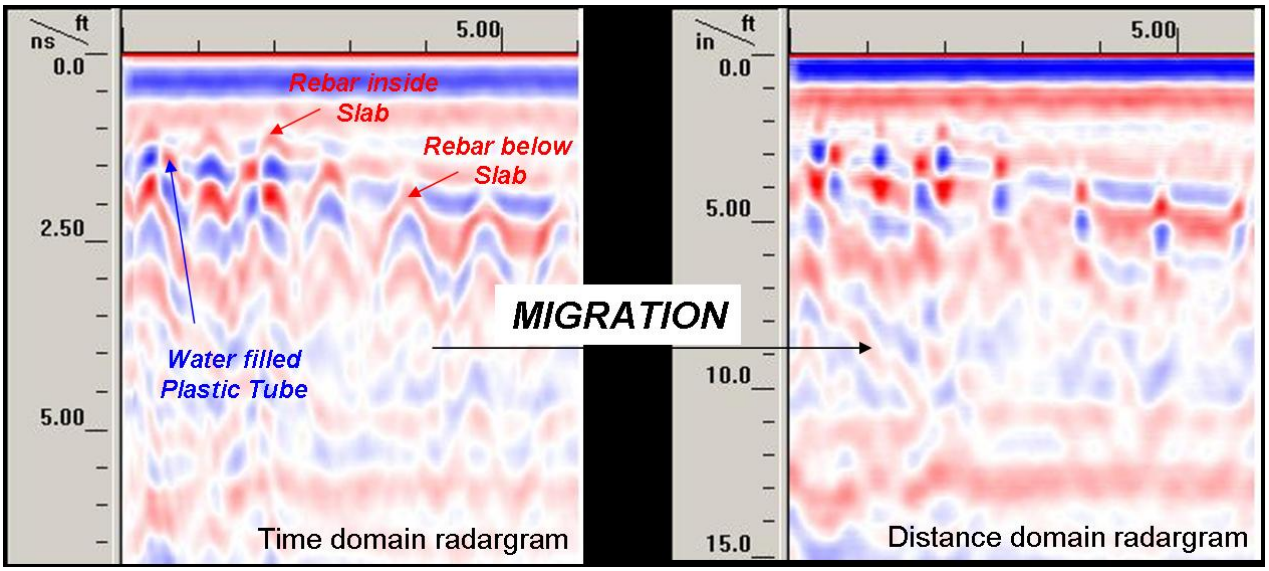


Figure 5 – Migrated GPR data of a Conventional Reinforced Slab-on-Grade Foundation System with a Floor Heating System

Figure 5 provides an example of differing hyperbolic shapes of steel reinforcements (rebar) within two different media. The red arrows mark several rebar positions. The time domain radargram depicts two visually different hyperbolas, one of which has a wider hyperbolic shape. The left red arrow depicts the reflective properties of rebar within a concrete section. The right red arrow depicts the reflective properties of rebar below the concrete section within a lower dielectric medium such as a dry sand since a medium having lower relative dielectric constant will produce wider hyperbolas. Geometric scaling and the migration of data were also performed to model the "real world" concrete section. Based on the migration method, the estimate propagation velocity (*V*) within the concrete was approximately 0.12 m/ns, which has a corresponding relative dielectric constant of 6.3. Given these estimated

dielectric parameters, the distance domain radargram was generated. Note how the hyperbolic shapes represent rebar, and water-filled tubing targets condense into points.

CASE HISTORIES

The Missing Reinforcement

The most notable construction and/or design defect documented in this paper occurred within a heavily loaded concrete pavement servicing a manufacturing facility. The concrete pavement shown in Figure 6 developed a series of significant cracks in various concrete sections. Some concrete sections exhibited no significant distress; whereas, adjacent concrete sections yielded numerous oblique cracking patterns. The formulated hypotheses prior to the GPR investigation ranged from horizontal and/or vertical placement concerns of the rebar to inadequate concrete strength. To evaluate the vertical and horizontal rebar placement within the concrete section, several GPR scans were performed across the concrete pavement. Proper horizontal and vertical rebar placement is represented by the hyperbolic shapes at the right side of the radargram in Figure 6. Note how the rebar is placed near the center of the concrete section, which is common. Observed concrete sections with no to minimal distress were shown to have proper vertical and horizontal steel placement as reflected at the right side of Figure 6.

However, as shown in Figure 6, rebar was not continuously present throughout the concrete pavement sections as evident by the lack of hyperbolic reflections. Observed concrete sections with moderate to high observed distress had no steel reinforcement.

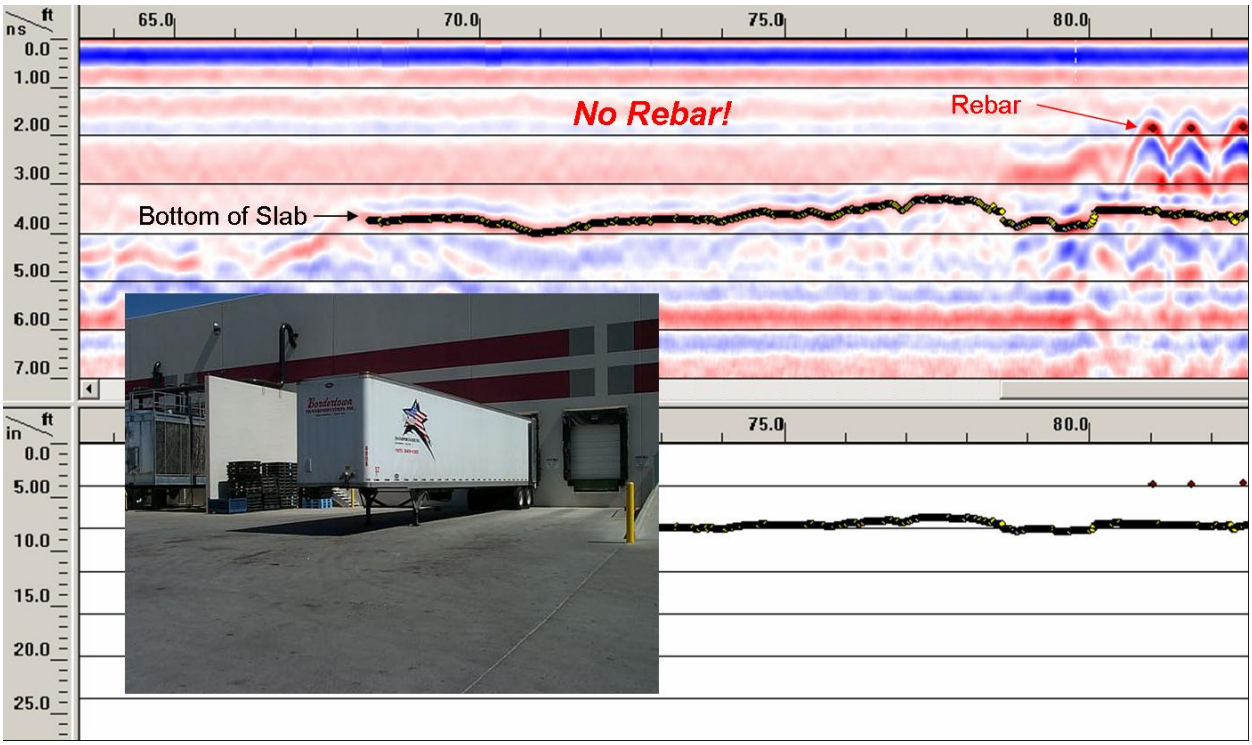


Figure 6 – Time-domain Radargram of a Heavily Loaded Traffic Pavement Servicing a Manufacturing Facility.

Structurally Suspended Concrete Floor Slab

The foundation system supporting the superstructure of a high school building consists of a structurally suspended foundation floor slab supported by interior/exterior grade beams and straight shafted, cast-in-place, concrete piers. Based on structural plans, an 8-inch separation between the foundation slab and underlying soils was specified using carton forms. However, a significant amount of upward movement occurred at the interior grade beams and certain sections of the floor slab. GPR was used to perform a concrete evaluation study of the foundation slab and determine the presence, or lack thereof, of the underlying voids.

Figure 7 shows a time-domain radargram across portions of the suspended slab with varying interfaces. The signal polarity, two-way travel time and reflection strength characteristics of this scan are important in the diagnosis of the concrete interfaces. The first third of the scan shows a strong negative reflection (blue) followed by a strong positive (red) reflection, which is indicative of an air-filled void beneath the concrete slab. The middle third of the scans recorded an opposite polarity (strong positive followed by strong negative) indicative of a water-filled void space. Soil contact with the foundation slab was encountered at the latter third. It was hypothesized (and confirmed) that the void space at this location collapsed due to heaving soils; and not during construction. If it had occurred during construction, the two-way travel time of the concrete section would have been significantly greater due to a thicker concrete section. The reflection strength at the concrete/soil interface is weaker with respect to the other two interfaces due to a lower dielectric

contrast between the two media. Based on Figure 7, the placement of reinforcement and depth of concrete were within project specifications.

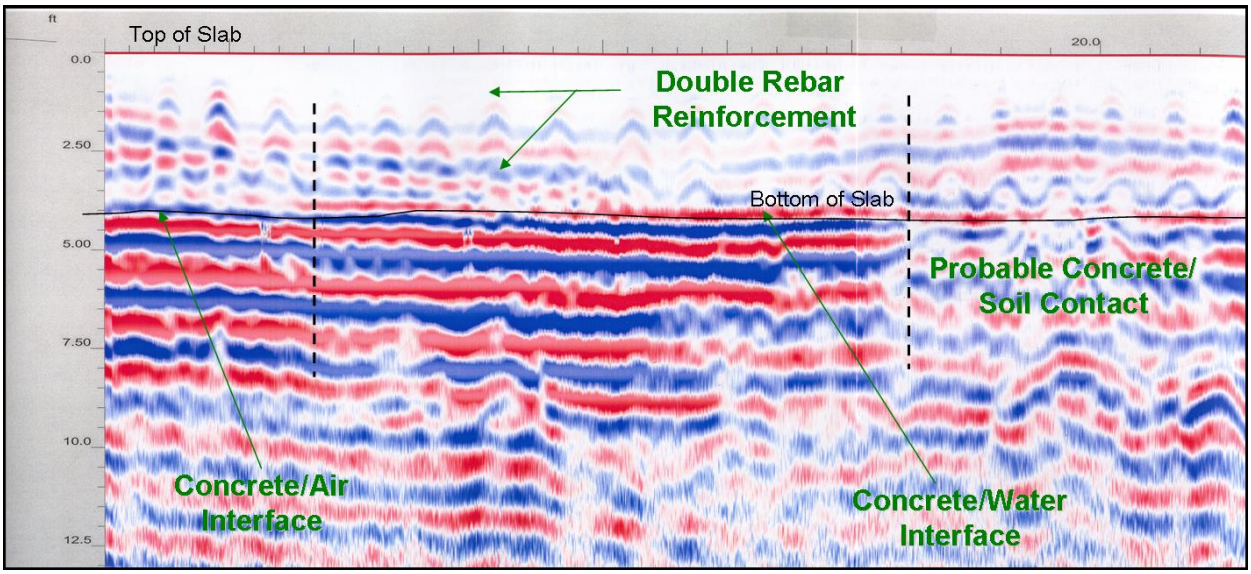


Figure 7 – Time-domain Radargram of Structurally Suspended Foundation Slab with Varying Concrete Interfaces.

A three-dimensional (3D) GPR survey was also performed across an interior grade beam, which had experienced upward movement and subsequent nearby superstructure distress at this location. Three-dimensional GPR survey lines are typically one to two feet on center. The model itself is compiled in highly robust visualization software capable of integrating large volumes of GPR data. Figure 8 plots the GPR data in a 3D format with respect to the foundation floor slab, interior grade beam and nearby column. The vertical scale is in inches and has been exaggerated by a factor of five for visualization clarity. Recent software advances has made three-dimensional model of GPR possible. However, additional development is much needed to further facilitate a user-friendly platform and expedite post-processing analysis. As indicated in Figure 8, the foundation slab thickness was on the order of 7 inches, which is near project specification. An air-filled void was present on both sides of the interior grade beam, as evident by a strong negative reflection (blue color) preceding a strong positive reflection (red color). However, the GPR data indicates that the interior grade beam width is approximately 26 to 30 inches throughout model as compared to a specified design width of 14 inches. This extended width may be attributed to over-pour at the interior grade beam and/or collapsed void space on either side of the interior grade beam. Whichever the case, the structural elements in close proximity to this interior grade beam were most likely in direct contact with the highly expansive supporting soils.

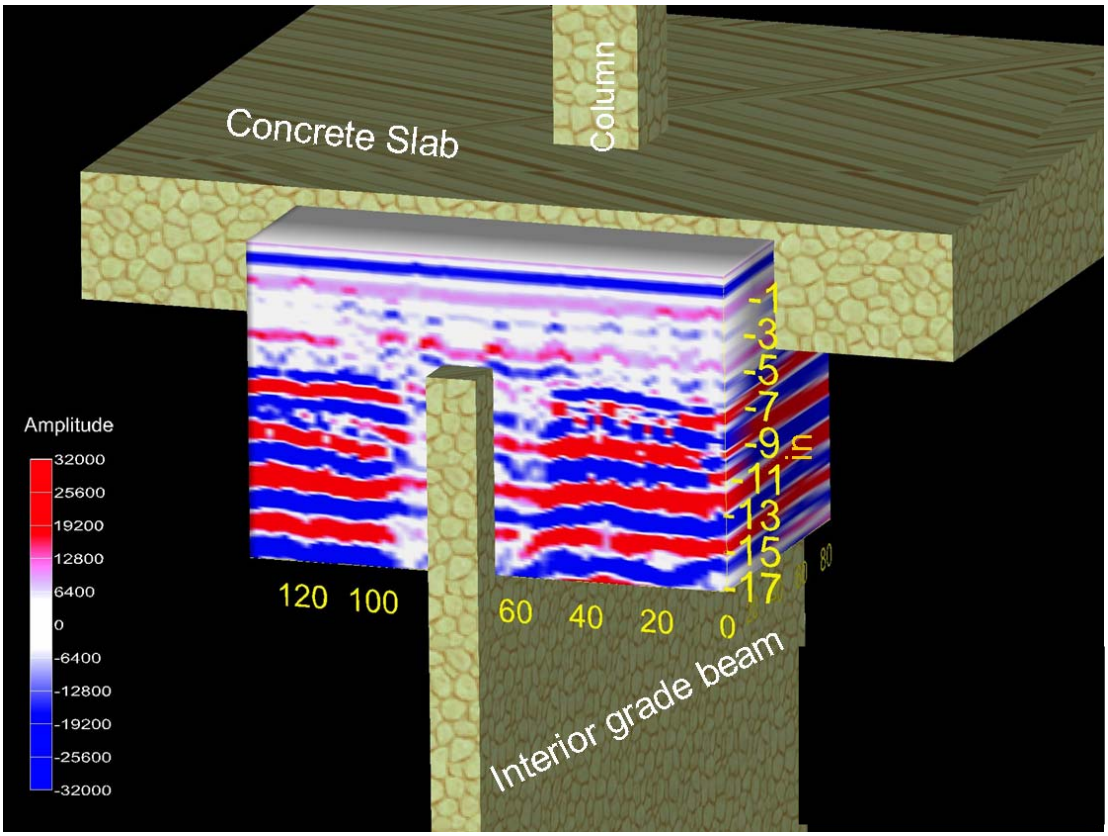


Figure 8 – 3D GPR Model of Interior Grade Beam

Utility Trench Settlement

Due to the improper compaction of backfill soils within utility trenches, settlement within these trenches is not uncommon. A concrete breakout in the hall bathroom revealed the presence of air-filled voids. GPR was used to spatially delineate the void space. Based on the GPR profile scans, localized void spaces underneath the concrete slab were located in the same vicinity of the utility trench. A typical void location map is shown in Figure 9. The documented air-filled voids beneath the foundation slab are marked by the hashed blue zones in Figure 9. The red arrows represent the GPR survey paths at this site. The secondary purpose of this investigation was to delineate the horizontal placement of post-tensioned steel cables within the concrete foundation slab unit. Based on the GPR investigation, the steel cables were approximately 5 to 6 feet on center.

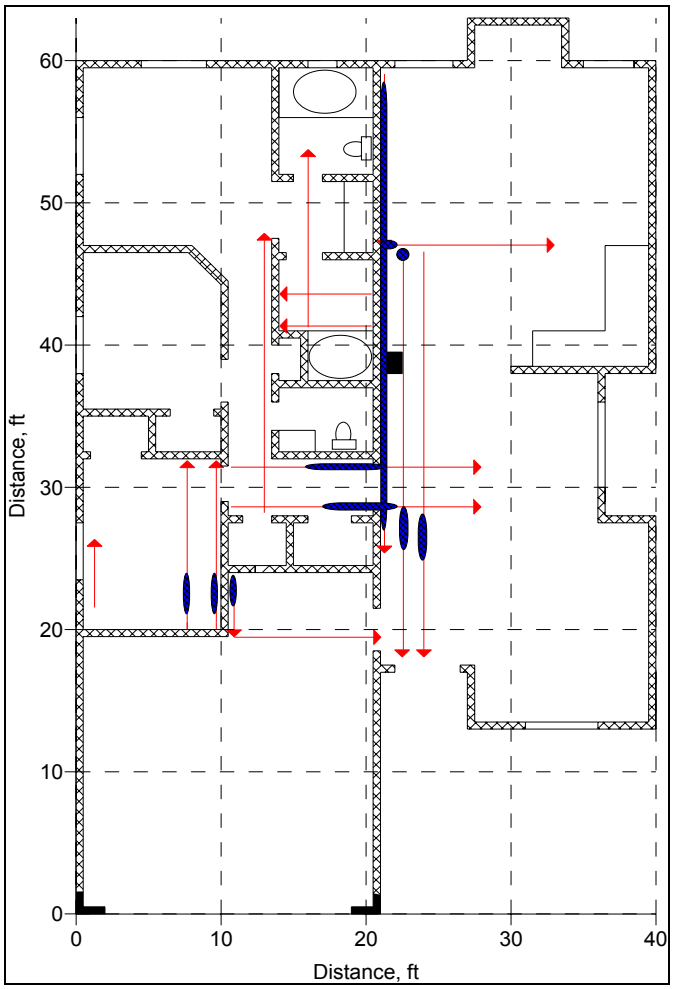


Figure 9 – Typical Void Detection Map

Figure 10 provides a representative migrated, distance domain radargram within the north hallway and dining room areas. Depth conversions are derived from hyperbolic geometric shape analysis using the migration method. The steel tendons were approximately 5 to 6 feet on center. As shown in Figure 10, the approximate slab thickness is five inches. An air-filled void is present underneath this section based on a strong negative-positive (blue-red) reflection. This was isolated to an approximate five foot section located just north of the hall bathroom during this profile scan, which corresponds to the utility trench location. The remaining section in Figure 10 reflects a typical concrete/soil interface (with similar dielectric properties) with no indications of subsurface voids. Note the lack of dielectric contrast between the concrete/soil interface, which makes slab thickness delineation and quantification difficult.

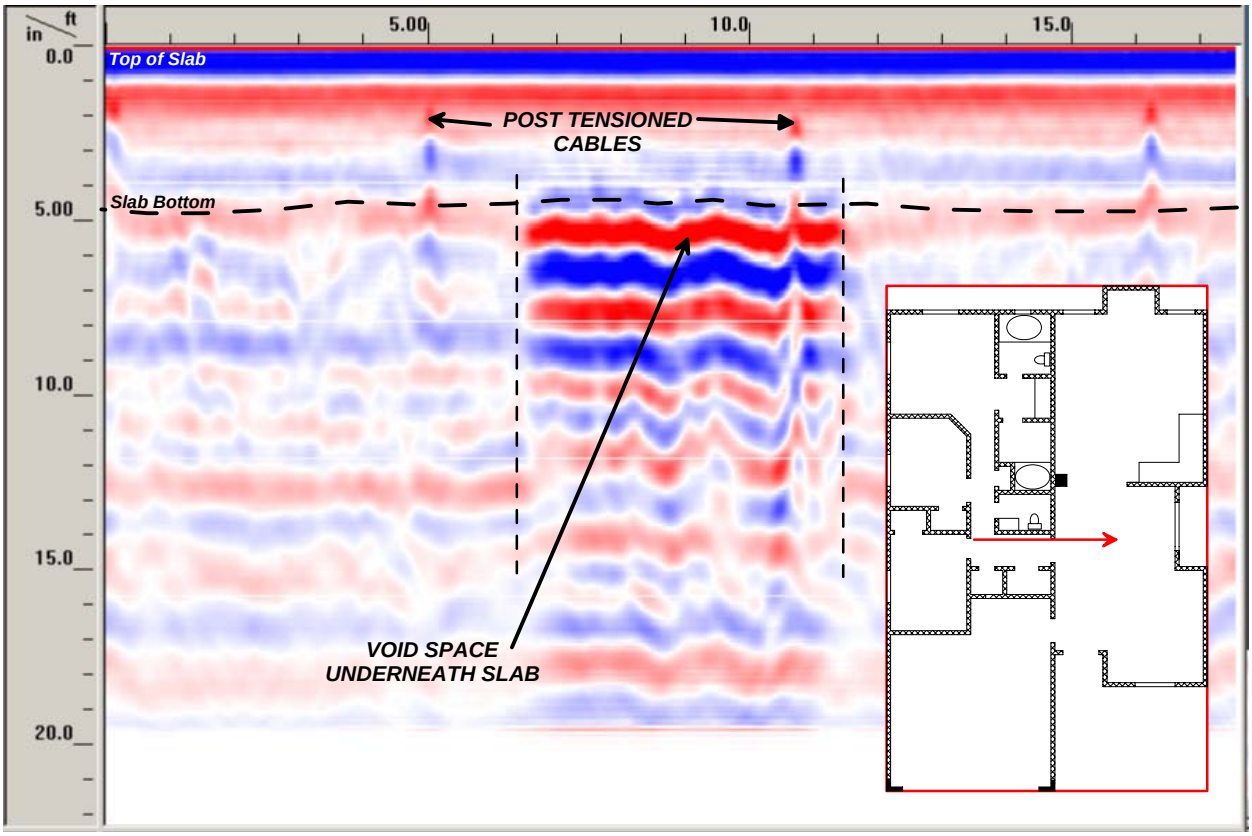


Figure 10 – Migrated, Distance-domain Radargram Model on a Slab-on-Grade Foundation System.

CONCLUSIONS

GPR provides an efficient and versatile means for concrete evaluation studies. Ideal electrical properties of concrete make exploratory studies using GPR extremely efficacious. Data collection and on-site cursory analysis are increasingly becoming easier with recent hardware improvements. More importantly, readily available GPR software has improved significantly, in particular for the concrete evaluation usage. Significant research and development has recently been applied to the determination of density and water content of each layer using GPR (Lytton, 1995). This is an added benefit for concrete evaluation studies. Three-dimensional modeling of GPR data is relatively new, but recent software advances using 3D processing and modeling are becoming more feasible and user-friendly. Current concrete evaluation studies involve the identification, qualification and/or quantification of reflected GPR signatures. These GPR signatures include, but may not be limited to, reflection strength, signal polarity, two-way travel time, signal attenuation and hyperbolic reflection, which is necessary for subsurface feature identification and/or delineation.

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