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GPR GOES UNDERGROUND: PIPE PENETRATING RADAR

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ABSTRACT: Pipe Penetrating Radar (PPR) is the underground in-pipe application of ground penetrating radar (GPR) either robotically or by manned entry to reveal wall thickness, delamination, voids, and other conditions that enable more precise determination of pipeline integrity and verifications for trenchless technology rehabilitation. PPR, when applied to pipe-bursting applications, can be used to detect metallic repair clamps and sleeves, reinforcing in concrete, thrust restraint and anchor blocks, and exterior sliplined host pipe casings. PPR also has the capabilities to confirm the presence of grouting applications between rehabilitation liners and outside pipe walls for ground stabilization and void elimination. PPR clearly identifies lateral locations behind rigid liners for reinstatement and reconnection.

This technology significantly impacts subsurface infrastructure condition based asset management by providing previously unattainable measurable conditions. This paper will summarize the PPR technology development, current methodology, identifying assessment applications, and illustrate how PPR presents critical structural information surrounding buried non-ferrous pipes.

1. INTRODUCTION

Deterioration of underground pipe infrastructure is a well documented fact (ASCE, 2009). Even though, they are the most basic resources sustaining urban life this underground network has largely been ignored, mostly due to the fact that it is invisible to the general public (Koo & Ariaratnam, 2006). The majority of the current underground pipe infrastructure was built over 50 years ago and is close to the end of its design life (ASCE, 2009). Recently the deterioration of this system has become a considerable financial burden to utility owners. Rehabilitation of the wastewater system requires extensive capital investments and the allocation of scarce resources must be prioritized. This leads decision makers to implement proactive preventative maintenance procedures. Proactive asset management allows utility owners to plan and schedule the inspection and rehabilitation of critical utilities prior to the occurrence of emergency scenarios (Koo & Ariaratnam, 2006). One of the most promising new quantitative pipe inspection and asset management methods is the in-pipe application of ground penetrating radar (GPR).

2. GROUND PENETRATING RADAR (GPR)

GPR is a high resolution electromagnetic technique that is designed primarily to investigate the shallow subsurface of the earth, building materials, roads and bridges. GPR is a time-dependent geophysical method that can also provide accurate depth estimates for underground objects, as well as a 3-D pseudo image of the subsurface. GPR uses the principle of emission, reflection and detection of electromagnetic waves in the radio frequency range (12.5 MHz to 4 GHz) to locate buried objects. The basic principles and theory of operation for GPR have evolved through the disciplines of electrical engineering and seismic exploration, and practitioners of GPR tend to have backgrounds in geophysical exploration. The fundamental principle of operation is the same as that used to detect aircraft overhead, but with GPR the antennas are moved over the surface rather than rotating over a fixed point. This has led to application of field operational principles that are analogous to the seismic reflection method (Daniels, 2000).

The application of GPR for the investigation of concrete structures is well known and has been in widespread use for a number of years (Annan et al., 2002; Bungey, 2004; Ékes, 2007). Applications for structural investigations commonly include locating spacing and depth of reinforcing steel, post-tensioning anchors, measuring rebar cover, mapping voids and clearing areas prior to cutting, coring or trenching (Bungey, 2004; Ékes, 2007). Structural applications include addressing the integrity of the concrete itself, such as the presence of voids, cracks, delamination or chemical alteration.

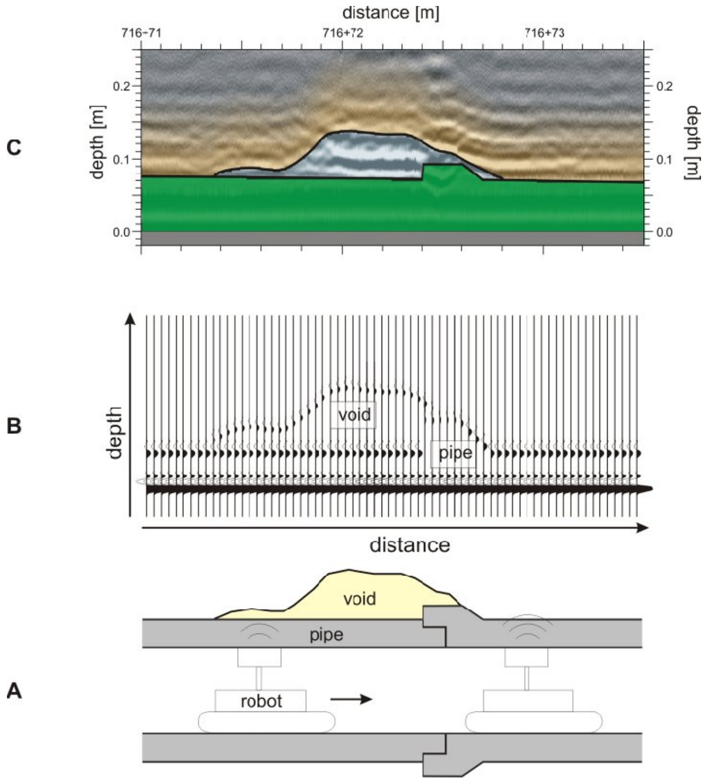

Figure 1. PPR Principle: A: robot mounted antennas continually emitting and recording pulsed GPR signals, B: signals are recorded as a series of A scans making up the corresponding radar “wiggle” trace (B scan), C: interpretation is superimposed on the processed radar plot.

3. PIPE PENETRATING RADAR FUNDAMENTALS

Pipe Penetrating Radar (PPR) is the underground in-pipe application of ground penetrating radar. The PPR pulse travels through a pipe material as a function of its electrical properties which are in turn a function of the materials’ chemical and physical composition. Some of this pulse will also be reflected and refracted by any sharp change in material properties, such as at the interface between pipe material and air or water. The greater the difference in the material properties, then the greater is the amount of energy reflected back. These reflected waves are detected by a receiving antenna and recorded as a single trace (A-scan). This process is repeated continuously as the antenna is moved along a survey line to build up an entire profile (B-scan) along the survey line (Figure 1). The radargram image is a display of transit time vs. distance traveled, with amplitude displayed either as a wiggle trace or colour scale. The recorded reflections can then be analyzed in terms of their shape, travel time and signal amplitude and phase.

Penetration depth is dependent on 1) the dielectric properties of the pipe and the host material, and 2) antenna frequency. The penetration depth of high frequency antennas (2.6 GHz - 500MHz) which are the most suitable for pipe investigations is on the order of 60cm to 3 m (2 ft to 9 ft) beyond the pipe wall. PPR resolution is defined as the smallest size feature which can be distinguished. Resolution is primarily determined by the wavelength, but is also affected by other factors such as polarization, dielectric contrast, signal attenuation, background noise, target geometry and target surface texture, all of which influence the reflected wave (Donazzolo & Yelf, 2009). As a general rule the thinnest layer that can be resolved is ¼ of the wavelength used. For a 2.6 GHz pulse travelling through a concrete pipe, this equates to approximately 9 to 15mm thickness. Once a layer is resolved, its thickness can be measured to a precision dependant on the time base sample rate and on the signal jitter of the GPR system used. For a depth range of 200mm (8 in) this can be as small as 4mm (1/8 in) (Donazzolo & Yelf, 2009).

PPR can be used to detect pipe wall fractures, changes in material, reinforcing location and placement, and pipe wall thickness. When used in conjunction with pipe rehabilitation technology, PPR can identify grout placement between pipe renewal systems and host pipes, liner bonding, and host pipe in-situ conditions including exterior repair clamps and soil variations for pipe-bursting replacement operations. PPR's primary use is to detect variation in pipe bedding conditions to identify the location and extent of voids outside pipe walls (Najafi, 2010). The technology can be deployed via manned entry or robotics (Figure 2).

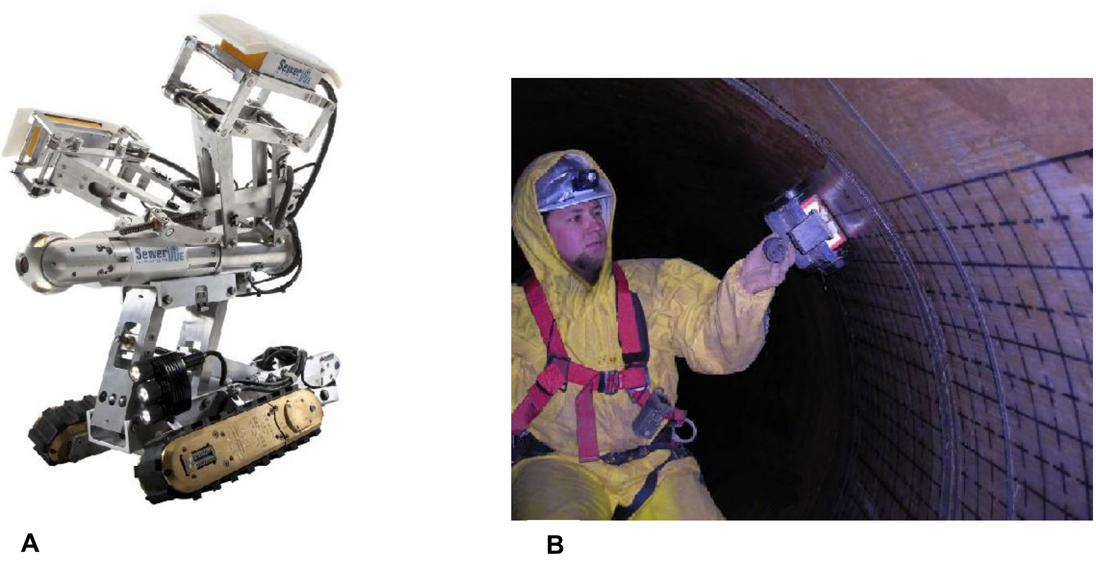

Figure 2. A: "SewerVUE Surveyor" multi-sensor inspection robot equipped with PTZ CCTV, and pipe penetrating radar. B: technician performing PPR scanning in a 60" (1800 mm) reinforced concrete water pipe.

4. DEVELOPMENT OF PIPE PENETRATING RADAR (PPR)

Starting in 2002, new, user friendly hardware and corresponding processing programs allowed non specialists to efficiently operate high frequency GPR systems that in turn made the technique feasible to operate within a pipe to provide for void detection and condition assessments of infrastructure that is nearing its safe service life. Early PPR attempts used rudimentary, project specific hardware that confirmed the viability of the technique. Below is a condensed history of in-pipe GPR in North America.

In 2004, The City of Phoenix approved a pilot project using a combined GPR and Digital Scanning & Evaluation Technology (DSET) system. The system carried one GPR antenna, and was limited to 750 mm (30 in) to 900 mm (36 in) pipe sizes. It could only inspect the pipe at the 12 o'clock position, and the maximum cable length was 75 m

(250 ft). With these limitations in place, approximately 1,800 m (6,000 ft) of pipe was inspected and the defects were located. This pilot project was the first documented successful use of this new technology for assessing large diameter lined concrete sewers (Ariaratnam et al., 2005). The use of GPR combined with DSET was found to be promising for detecting defects in the concrete pipe wall behind the PVC liner. Ariaratnam et al. (2005) speculated that as this technology advances, it could have other applications including the assessment of reinforcing bars within a pipe wall and determination of pipe wall thickness.

In 2005, GPR was used to assess the tunnel lining condition and locate concrete deterioration and voids in the 9 km long Kapoor Water Supply Tunnel, Victoria, BC, Canada, using a GPR system mounted on a custom built cart. The major GPR anomalies were drilled to verify interpretations of voids behind the liner. Five major types of anomalies were identified: variations in water content, void spaces, embedded wood, faults and metallic objects. The 17.58 km GPR data taken in the 2.3 m diameter tunnel showed that GPR continuously mapped concrete liner thickness, presence of reinforcement and delineated zones where mesh roof supports and construction support timbers are embedded in the liner, as well as the locations and orientations of faults that intersect the tunnel. Minor voids, honeycomb sections and areas of rock-liner separation were also detected (Parkinson & Ékes, 2008)

In 2009, the City of Hamilton, ON, Canada, conducted an in-pipe man entry inspection to verify 1998 field data as well as include an assessment of the sewer's structural integrity. This included exploration of pipe wall thickness and concrete strength verification. GPR was used to detect voids outside of the pipe walls. While using GPR to locate external voids, the team discovered voids within the pipe wall as well, likely a result of the concrete pouring practices used in the 1960's (Bainbridge et al., 2010).

In 2010, the Weber Basin Water Conservancy District in Layton, Utah commissioned a high frequency GPR survey to investigate four interior joints of the 60-inch unlined RCP raw water Davis Aqueduct. The GPR survey successfully mapped pipe wall thickness, rebar spacing and depth, ascertained the joint configuration and located voids outside of the pipe (Figure 2, SewerVUE, 2010a).

5. THE SEWERVUE SURVEYOR PPR SYSTEM

GPR equipment consists of antennas, electronics and a recording device. They are digitally controlled and data are usually recorded for post survey processing and display. The digital control and display part of a GPR system most commonly consists of a micro-processor, memory and a mass storage medium to store the field measurements. A micro-computer and standard operating system is often utilized to control the measurement process, store the data and serve as a user interface (Daniels, 2000).

Standard "above ground" data collection techniques can be utilized in pipe inspection when manned entry is feasible (Parkinson & Ékes, 2008) or when the pipe is exposed (Donazzolo & Yelf, 2009). Running a remotely controlled GPR survey in an underground pipe creates special challenges, since the commercially available systems are not designed to transmit data over long distances, the length of the data cable is typically 4 metres (12 ft). Frequency selection, triggering and positioning is also problematic.

In 2009, Terraprobe Geoscience Corp., a GPR service provider assisted by Canada's National Research Council (NRC) developed a robotic inspection vehicle for condition assessments of buried infrastructure. They developed a commercial grade, robot mounted, modular, multi sensor inspection tool (SewerVUE Surveyor) that consisted of two independently controllable high frequency antennas that can be adjusted between 18 in. (450mm) and 36 in. (900mm) pipe diameter and can scan the pipe wall between 9 o'clock and 3 o'clock position with a maximum tether length of 6000 feet (SewerVUE, 2010b). The development team overcame the challenge of antenna positioning, triggering and data communication over large distance and created a user friendly interpretation and reporting interface (PP RADIAN). The robot was successfully tested in a variety of pipes sizes with varying level of flow.

The SewerVUE Surveyor provides quantifiable results such as pipe wall thickness and rebar cover for buried infrastructure structural condition assessments. Pan/tilt/zoom CCTV completes the multi–sensor inspection (MSI) package on the Surveyor and provides for a visual, standards coded reference commonly accepted as the minimum in any condition assessment. Currently, this is the only commercially available system on the market (USEPA, 2010).

6. DATA DISPLAY AND INTERPRETATION

The objective of PPR data presentation is to provide a display of the processed data that closely approximates an image of the pipe and its bedding material with anomalies that are associated with the objects of interest in their proper spatial positions. Producing a good data display is an integral part of interpretation (Daniels, 2000).

There are five types of data display: 1) a one-dimensional trace or A scan, 2) a two dimensional cross section or B scan, 3) a two dimensional depth slice (plan view map) or C scan, 4) a three dimensional display, and 5) an integrated pipe penetrating radar data display (IPPRDD).

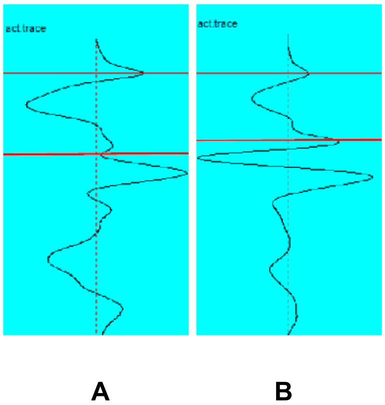

Figure 3. A-scan traces: A) a water filled asbestos cement pipe, 41mm wall, B) air filled asbestos cement pipe, 37mm wall. From Donazzolo & Yelf (2009) with permission.

A wiggle trace (or scan) is the building block of all displays. A single trace can be used to detect targets and determine their depth below a spot on the pipe. By analyzing A-scan traces Donazzolo & Yelf (2009) were able to accurately measure changes in AC pipe wall thickness with 4 mm accuracy in a study conducted on water pipes in Australia (Figure 3).

Cross sections can be wiggle trace displays or more commonly grey-scale or color scans (Figure 4). By moving the antenna over a pipe wall and recording traces at a fixed spacing a section of traces is obtained. The horizontal axis of the record is antenna position and the vertical axis is the two way travel time of the EM wave (Figure 1, 4). A PPR record is very similar to the display of seismic reflection or the display for a fish finder. A scan display is obtained by assigning a color to amplitude ranges on the trace.

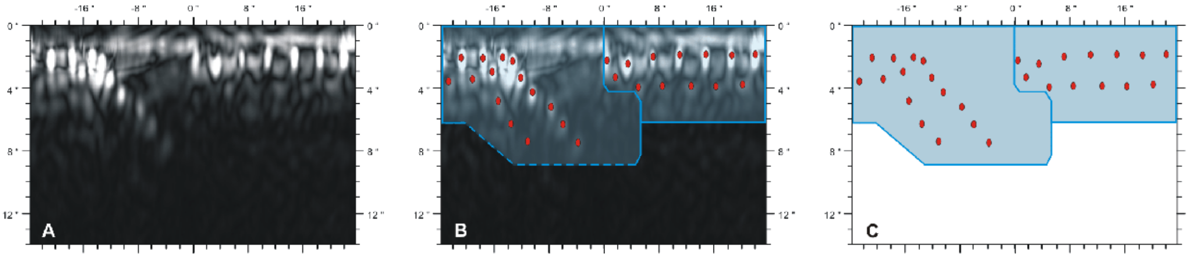

Figure 4. PPR cross section (B-Scan) showing joint configuration in a 60 inch reinforced concrete pipe. A: processed and migrated PPR data, B: processed data with interpretation overlay, C: interpretation. Red dots represent rebar. Scale in inches.

Grid scans (plan view maps or C-scans) can be obtained by combining cross sections (line or B-scan). Grid scans are generally more readily understood by a non-specialist engineer (Figure 5). 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 pipe. Targets with great conductivity contrast (metallic targets, such as wire mesh, rebar and repair clamps) can be located and identified with relative ease, while less conductive targets, such as air voids, honeycombing and delamination can sometimes be obscured by reflections emanating from rebar. Good survey procedures and advanced data processing are imperative for detecting such targets.

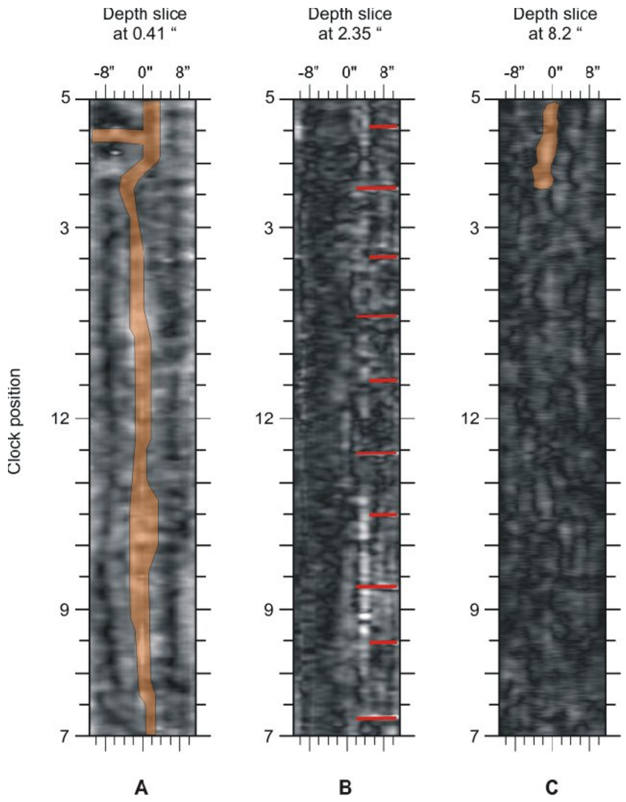

Figure 5. Selected time (depth) slices of a 60" RC pipe joint. Orange areas at the joint (0" position) indicate voids within the pipe (A). Horizontal (red) lines represent reinforcing steel (B). Orange area represent void outside the pipe at the invert (C).

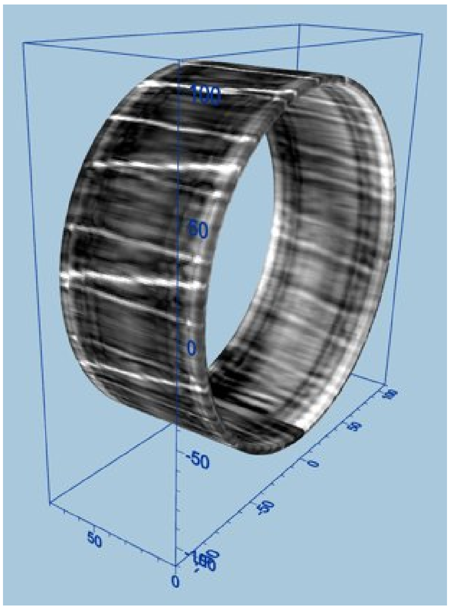

Figure 6. 3D view of a 42" RC pipe joint, white bands and lines represent rebar.

Three dimensional displays are fundamentally block views of PPR traces that are recorded at different positions on the pipe surface. Data are usually collected along profile lines, the accurate location of each trace is critical to producing accurate 3D displays. Normally, 3D block views are constructed from several parallel, closely spaced lines as shown in Figure 6. Once the blocks are constructed, then they may be viewed in a variety of ways, including as a solid block or as block slices or as animated transparent 3D objects.

Obtaining a good three dimensional display is a critical part of interpreting PPR data. Targets of interest are generally easier to identify and isolate on three dimensional data sets than on two dimensional profile lines. Simplifying the image by eliminating the noise and clutter is the most important factor for optimizing the interpretation. This is normally achieved through data processing by: 1) assigning the amplitude-color ranges, 2) displaying only one polarity of the GPR signal, 3) using a limited number of colors, 4) reducing the size of the data set that is displayed as the complexity of the target increases, 5) displaying a limited time range (finite thickness time slice), and 6) carefully selecting the viewing angle (Daniels, 2000). Further image simplification can be achieved by displaying only the peak values (maximum and minimum values) for each trace.

The first commercially available integrated "**Pipe Penetrating Radar Data Interpretation Application (PP-RADIAN)**" data processing and display package was released in March 2010 (SewerVUE, 2010c) by SewerVUE Technology Corp. This application allows 3D visualization of key pipe attributes such as pipe wall thickness, substrate voids and rebar configuration in reinforced concrete pipes. PP-RADIAN splices individual radar scan lines into a spatially corrected 3D representation, which can then be viewed at 1/16 inch (2 mm) depth intervals. This approach allows the display of the highest theoretical resolution of GPR data possible to provide confident assessment of joint configuration, pipe wall thickness and rebar cover.

In the reporting function the PPR results are displayed with the interpretation superimposed on the actual depth profiles versus distance (Figure 7A). The top 4 lines show the individual PPR profiles with the corresponding clock position and antenna frequency denoted with an icon to the left of the corresponding profile. The scales are in metres. The location of the scan lines are marked on the foldout view of the pipe at the bottom of each pipe segment with the corresponding clock positions on the vertical axis. Anomalies and other notable features are color coded.

Vertical dashed lines denote the location of the pipe cross sections (Figure 7B) The cross sectional view of the pipe shows the interpreted pipe wall thickness and other pertinent information at the given chainage together with the foldout view of the pipe.

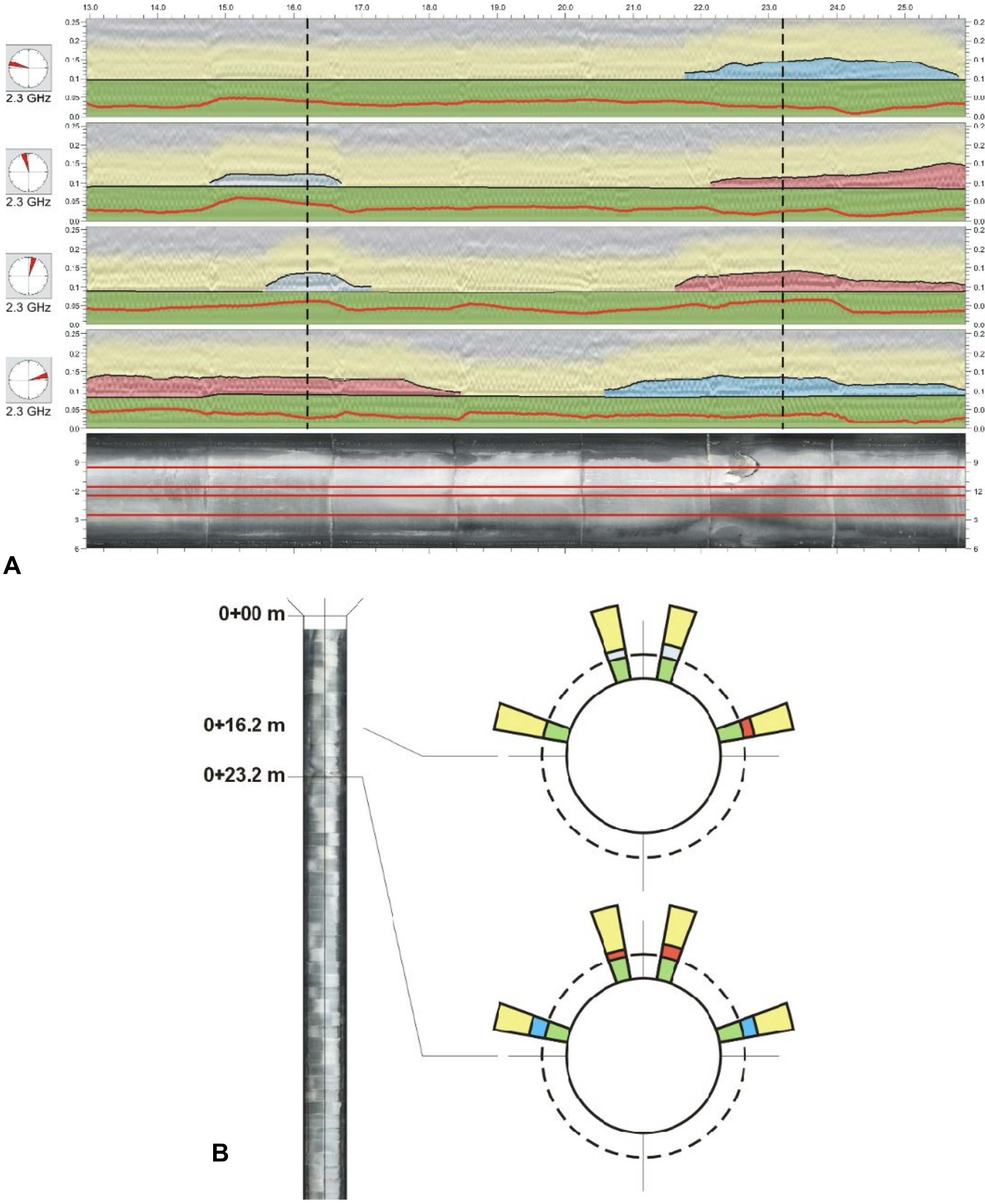

Figure 7. PP RADIAN views of a 30” (750mm) reinforced concrete sewer pipe: A: longitudinal cross sections at multiple clock positions with corresponding CCTV foldout view. B: Cross section view with corresponding CCTV foldout view.

7. DISCUSSION AND CONCLUSIONS

Condition assessments using multiple surveys over time can yield extremely important trending data that can assist in determination of an asset’s remaining safe service life, advancement of voids, and quality control for manufactured pipe by assessing surveyed wall deterioration (USEPA, 2010). Pre and post construction installation as well as establishment of an installed asset’s baseline measurements can also be determined, as can be warranty inspections for pipe rehabilitation technologies. One of the most promising new condition assessment technologies is the in pipe application of GPR or pipe penetrating radar (PPR). Recent developments of this emerging technology are documented in this paper and its capabilities are demonstrated through examples from well documented case studies. This paper also explored the relatively little understood aspect of data processing and display function of PPR, the understanding of which is crucial for accurate data interpretation.

Pipe Penetrating Radar (PPR) is the underground in-pipe application of ground penetrating radar (GPR) either robotically or by manned entry to reveal wall thickness, delamination, voids, and other conditions that enable more precise determination of pipeline integrity and verifications for trenchless technology rehabilitation. PPR, when applied to pipe-bursting applications, can be used to detect metallic repair clamps and sleeves, reinforcing in concrete, thrust restraint and anchor blocks, and exterior sliplined host pipe casings. PPR also has the capabilities to confirm the presence of grouting material between rehabilitation liners and outside pipe walls for ground stabilization and void elimination. PPR has the ability to identify lateral locations behind rigid liners for reinstatement and reconnection. This technology significantly impacts subsurface infrastructure condition based asset management by providing previously unattainable measurable conditions.

Just as GPR has become a routine survey tool for the location of embedded elements such as rebar and post-tension cables in structural assessment for “above ground” concrete structures, PPR has the potential to achieve very similar status for underground non-ferrous pipes within the next few years. Advances in sensor technology, data interpretation via sophisticated software using ever increasing speed and processing power, and acceptance by the engineering community will ensure that structural condition assessments using PPR will become more prevalent. Information and technology gaps identified by the USEPA in 2010 will rapidly be addressed to the benefit of owners of underground assets.

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