Completing Condition Assessments using In-pipe GPR as Pipe Penetrating Radar

Csaba Ékes, Boriszlav Neducza, and Gordon R. Henrich

SewerVUE Technology Corp., 4650A Dawson St., Burnaby, BC, Canada V5C 4C3; Tel: 1-888-973-9378, email: info@sewervue.com

Abstract

This paper describes the development of Pipe Penetrating Radar (PPR), the underground in-pipe application of GPR, a non-destructive testing method that can detect defects and cavities within and outside mainline diameter (>18 in / 450mm) non-metallic (concrete, PVC, HDPE, etc.) underground pipes. The method uses two or more high frequency GPR antennae carried by a robot into underground pipes. The radar data is transmitted to the surface via fibre optic cable and is recorded together with the output from CCTV (and optionally sonar and laser). Proprietary software analyzes the data and pinpoints defects or cavities within and outside the pipe. Thus the testing can identify existing pipe and pipe bedding symptoms that can be addressed to prevent catastrophic failure due to sinkhole development and can provide useful information about the remaining service life of the pipe. The key innovative aspect is the unique ability to map pipe wall thickness and deterioration including cracks and voids outside the pipe, enabling accurate predictability of needed intervention or the timing of replacement.

This reliable non-destructive testing method significantly impacts subsurface infrastructure condition based asset management by supplying previously unattainable measurable conditions.

INTRODUCTION

Underground pipe infrastructure including tunnels and culverts is deteriorating at an alarming rate (ASCE, 2009). The majority of the current underground pipe infrastructure was built over 50 years ago and is close to the end of its design life. In order to establish the extent of rehabilitation or the timing of replacement an internal inspection method is necessary. Although CCTV is an effective tool for identifying visible defects on the internal wall of pipelines it cannot see behind the pipe's inner surface. In order to overcome this limitation and provide utility owners and decision makers with a quantitative and predictive inspection and asset management tool the in-pipe application of ground penetrating radar (GPR) has been developed that allows the implementation of proactive preventative maintenance procedures for non-ferrous wastewater and water underground infrastructure. 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).

This paper describes the principles of PPR, recent hardware and software developments, some of its applications and concludes with a brief summary of current research.

FROM GPR TO PPR

GPR is a high resolution electromagnetic technique that is designed primarily to investigate the shallow subsurface of the earth, building materials, roads and bridges. It 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. As Daniels (2000) aptly pointed out, early practitioners of GPR tended to have backgrounds in geophysical exploration.

This started to change in 2002 when new, user friendly hardware and corresponding processing programs allowed non specialists to efficiently operate high frequency GPR systems. Faster processors allowed efficient data collection in applications such as concrete scanning, utility location, highway pavement or bridge deck cover mapping often at highway speeds. These surveys were sometimes conducted by unsophisticated operators who lacked the understanding of the fundamental principles and limitations of the GPR profiling method. Understanding the physics and limitations of the GPR method together with proper data collection and data processing protocol are the key to successful data interpretation. GPR as any other geophysical technique is science, data interpretation accuracy depends on the right processing software and relevant user training and experience.

The earliest reported in pipe GPR survey took place in 2004 when the city of Phoenix, AZ approved a pilot project using a combined GPR and Digital Scanning & Evaluation Technology (DSET) system. The system carried one GPR antenna, suitable to 750 mm (30 in) to 900 mm (36 in) pipe sizes with the maximum cable length of 75 m (250 ft) and inspected approximately 1,800 m (6,000 ft) of pipe and located the defects at the 12 o'clock pipe position (Ariaratnam et al., 2005). The authors 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. The 18 km long GPR data collected 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). More recently Crowder et al. (2010), Ratliff & Russo (2010) and Ékes et al. (in press) reported successful manned entry applications of PPR.

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 dielectric 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).

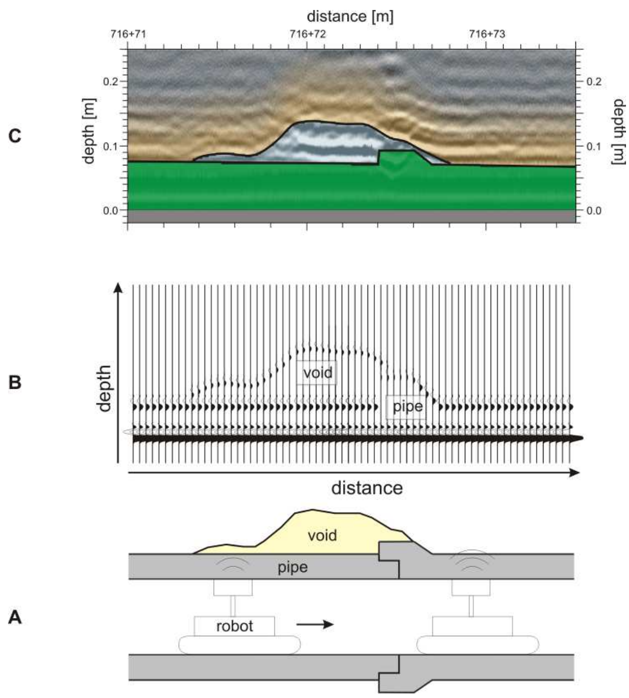

Figure 1. PPR Principle: A: robot mounted antennas continually emitting and recording pulsed GPR signals, B: signals are recorded as a series of A scans making up the corresponding radar "wiggle" trace (B scan), C: interpretation is superimposed on the processed radar plot.

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 be then be analysed in terms of their shape, travel time, signal amplitude and phase.

Signal penetration depth is dependent on the dielectric properties of the pipe and the host material, and on the antenna frequency. The penetration depth of high frequency antennas (2.6 GHz – 500 MHz) which are the most suitable for pipe investigations is on the order of 60 cm to 3 m (2 ft to 9 ft) beyond the pipe wall. Resolution is primarily determined by the wavelength, but is also affected by other factors such as polarisation, dielectric contrast, signal attenuation, background noise, target geometry and target surface texture, all of which influence the reflected wave. 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 4 mm (1/8 in) (Donazzolo & Yelf, 2009).

Since the primary factor determining signal penetration is the conductivity of the soil, it is important to point out that PPR works where traditional “above ground” GPR does not. If for example, there is a pipe buried in conductive soils (more than 58% of USA and Canada) at 1.8 m (6 ft) depth or deeper, the signal from “above ground” GPR most likely will not penetrate the soil for more than 0.6 m (2 ft). In-pipe GPR signals, however, will penetrate non-ferrous pipe walls, the pipe bedding and even the conductive soil to some degree mapping air or water filled voids on the way from within the pipe. In most cases, native soil conditions in specific geographic locations have little bearing on detection of voids outside pipelines because bedding and backfill tend to be coarse grained with favorable dielectrical properties.

DEVELOPMENT OF MULTI-SENSOR INSPECTION ROBOT INCLUDING PPR

Several case studies have demonstrated that manned entry PPR inspections provide otherwise unobtainable information on the condition of the pipes. Since manned entry is often not feasible or possible the combination and integration of two or more inspection technologies onto a robotic platform including critical sensors (e.g., CCTV, sonar and laser scanners) has been attempted and some of these multi-sensor inspection robots have been commercialized in various forms in Europe, North America, Japan and Australia (USEPA 2010).

Figure 2. Fourth generation multi-sensor inspection robot equipped with pan, tilt, zoom CCTV, LIDAR and pipe penetrating radar.

The first commercially available PPR system was developed and commercialized as a multi-sensor inspection (MSI) robot that uses visual and quantitative technologies (CCTV, LIDAR, and GPR). This fourth generation GPR pipe inspection system is mounted on a rubber tracked robot and equipped with two high-frequency GPR antennae (Figure 2). The system can be adjusted between 18- and 36-inch (450 to 900mm) diameter pipe, while the GPR antennae can be rotated between the nine and three o'clock positions. Radar data collection is obtained via two independent channels in both in and out directions, providing a continuous reading on pipe wall thickness, rebar cover and locating voids outside the pipe. CCTV data is recorded simultaneously and is used for correlation with GPR data collection. The robot is also outfitted with LIDAR capabilities to map quantitative measurements of inside pipe walls (Figure 3). This technology employs rotating laser to collect inside pipe geometric data which is then used to determine pipe wall variances from a manufactured pipe specification. LIDAR data is correlated with an onboard inertial navigation system (INS) that can accurately map the x, y, and z coordinates of the pipe without the need for external references.

The unit is equipped with three cameras (front, antenna and back). Maximum tether length is 6,000 feet. Optional condition assessment technology that can be added as additional payload include continuous H_2S Gas Monitoring and other atmospheric condition recording equipment. The unit provides quantifiable results such as pipe wall thickness and rebar cover for buried infrastructure structural condition assessments.

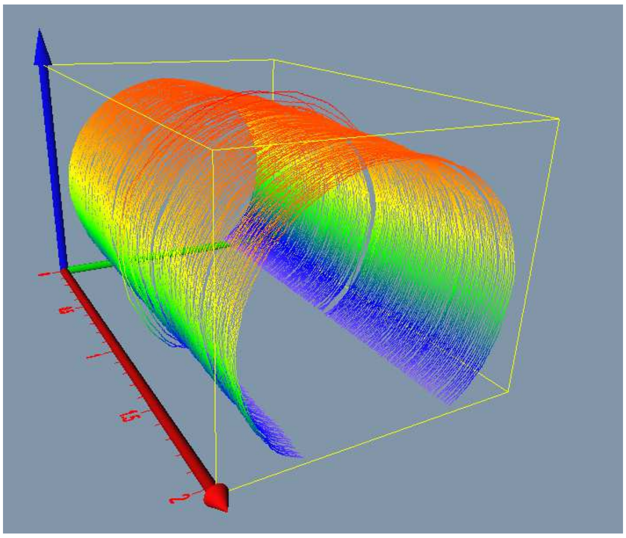

Figure 3. 3D view of a 24” plastic pipe joint generated from laser data.

PPR 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 the step after data processing and is an integral part of interpretation (Daniels, 2000). Processing of in pipe GPR data is an involved subject and is beyond the scope of this paper. The interested reader is referred to Daniels (2004).

The five types of data display are reviewed by Ékes at al. (in press). The most commonly used data displays are the two dimensional cross section or B scan (Figure 4), the two dimensional depth slice (plan view map) or C scan, and the relatively new three dimensional display. The integrated pipe penetrating radar data display (IPPRDD) pioneered by Ékes et al. (in press) is the most comprehensive.

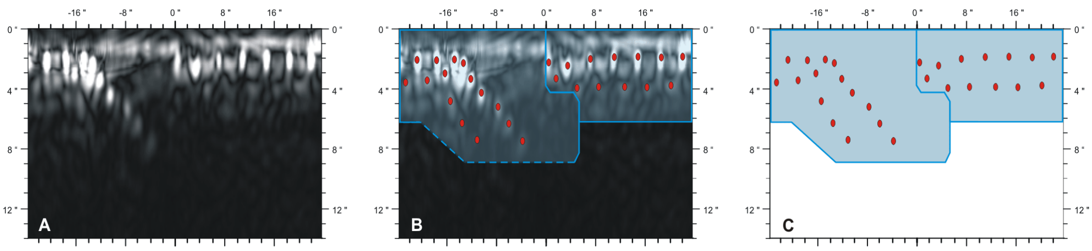

Figure 4. PPR cross section (B-Scan) showing joint configuration in a 60 inch reinforced concrete pipe. A: processed and migrated PPR data, B: processed data with interpretation overlay, C: interpretation. Red dots represent rebar. Scale in inches.

In the reporting function of the integrated pipe penetrating radar data display (IPPRDD) PPR results are displayed with the interpretation superimposed on the actual depth profiles versus distance (Figure 5). 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. Currently this is the most advanced and comprehensive way of reporting PPR results (Figure 5).

Vertical dashed lines denote the location of the pipe cross sections (Figure 5B) 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.

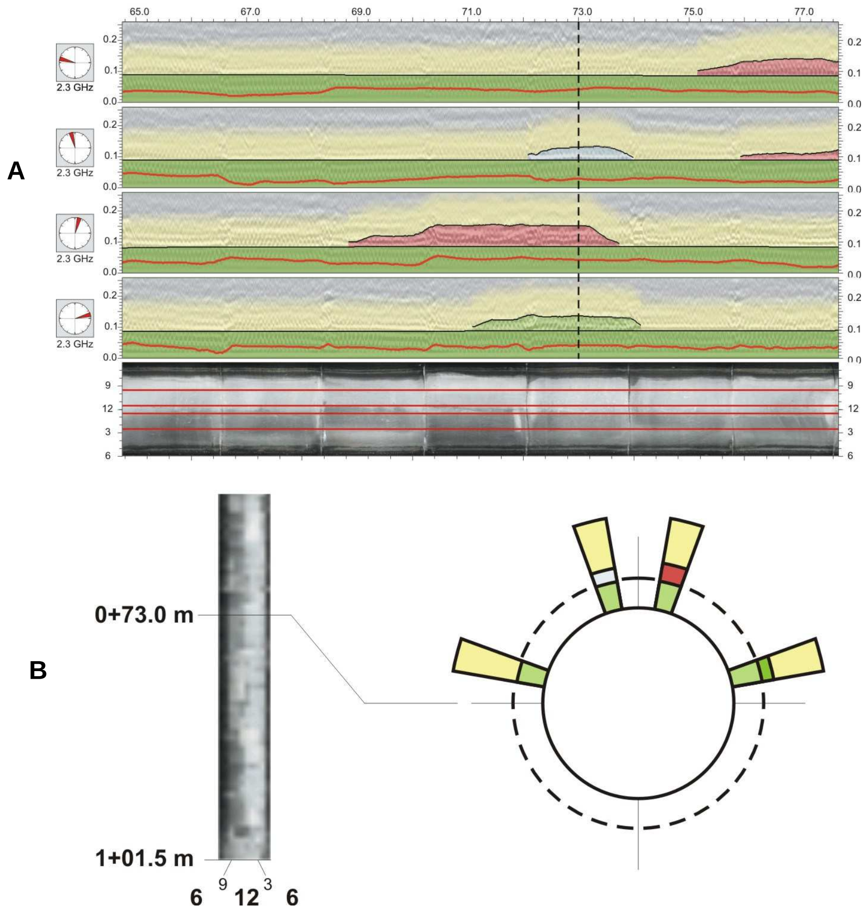

Figure 5. PP RADIAN views of a 30” (750mm) reinforced concrete sewer pipe: A: longitudinal cross sections at multiple clock positions with corresponding CCTV foldout view. B: Cross section view with corresponding CCTV foldout view.

PIPE PENETRATING RADAR ASSESSMENT APPLICATIONS

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).

PPR can provide a better understanding of expected life cycle and deterioration rates for the proper use asset management systems. PPR can also fill some key gaps as an improved nondestructive inspection and condition assessment tool, enabling assessment of thickness and material properties for pipe liners and identification of annular gaps between the liner and the host pipe.

OTTLEY CREEK, PORT MOODY, BC, CANADA CASE STUDY

Greater Vancouver Sewerage and Drainage District commissioned a high frequency pipe penetrating radar (PPR) survey to investigate a rectangular 30" storm-sewer pipe in Port Moody, BC, Canada. The objective of the survey was to confirm the existing pipe wall thickness and locate any unforeseen obstacles or obstructions below the invert of the existing pipe by using PPR. Since no information was available about the construction method and the condition of the pipe PPR data provided critical baseline information for selecting the appropriate maintenance and rehabilitation strategy. A simultaneous CCTV recording accompanied the survey in order to provide a visual record of the inspection.

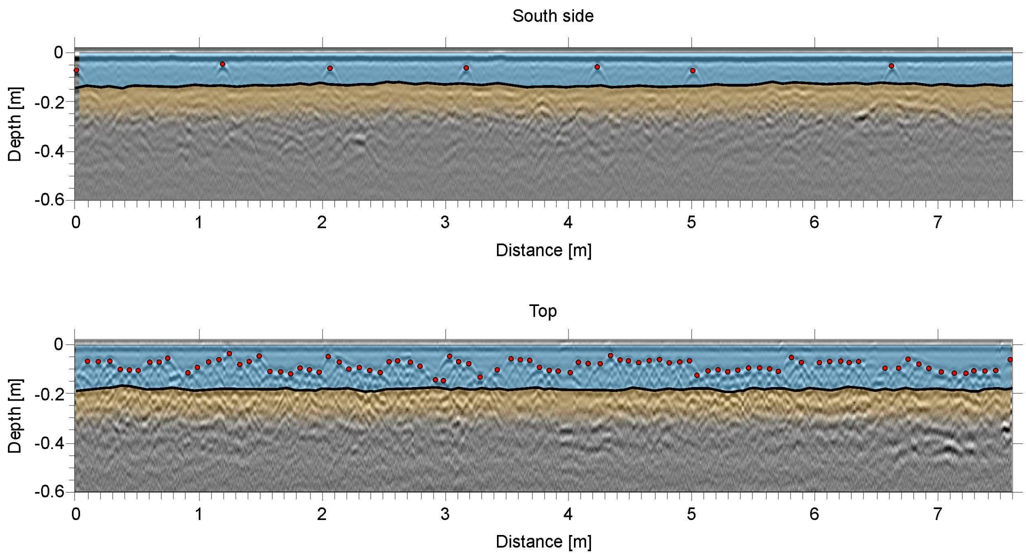

Figure 6. Interpreted PPR data from a) side wall, and b) obvert of the 30” box culvert in Port Moody, BC. Pipe wall thickness is marked by black line, rebar is represented by red dots.

The PPR data was of excellent quality with 400-600 mm (16”-24”) signal penetration. The interpreted GPR depth sections are shown in Figure 6. Pipe wall thickness is marked by a continuous black line, reinforcement is marked by red dots.

PPR results indicate that the thickness of the concrete side walls varies between 100 and 180 mm (4” and 7”). The top of the pipe is 200 mm (8”) thick and it is more or less uniform in thickness. Reinforcement is dramatically different between the side walls and the obvert. There is generally 1 rebar per meter in the side walls, however, the top of the pipe is better reinforced with rebar at every 80 mm. The PPR survey concluded that the concrete section of the culvert appears to be in good condition and that the 200 mm thick obvert of the culvert appears to have been constructed of reinforced concrete beams.

CONCLUSIONS AND CURRENT RESEARCH

PPR has demonstrated early successes as a standalone pipe inspection system operated both in manned entry and remote robotic mode. Current research is underway to investigate the feasibility of in-pipe use of UWB antennas which circumvent the need for having the antennas placed in contact with the pipe wall (Jaganathan et al., 2006).

The next step in the continuing development of hardware system is to combine the output not only from CCTV with PPR but incorporate Lidar and accurate x, y, and z positioning, and optionally sonar data into a comprehensive reporting package. The hardware is already in the market (Figure 2) the processing and visualization software has been developed and passed the pilot phase. Commercial rollout has begun in February 2011.

Condition assessments using multiple surveys over time can yield extremely important trending data that can assist in determination of an assets 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 hardware and software developments of this emerging technology are presented in this paper and its capabilities are demonstrated through examples from recent case studies.

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