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Quantitative pipe condition assessment with Pipe Penetrating Radar

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1. ABSTRACT

Pipe Penetrating Radar (PPR) is 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-ferrous (reinforced concrete, vitrified clay, PVC, HDPE, etc.) pipes. The key advantage of PPR is the unique ability to map pipe wall thickness and deterioration including voids outside the pipe, enabling accurate predictability of needed rehabilitation or the timing of replacement.

This paper presents recent advancement of PPR inspection technology together with selected case studies. Two case studies are discussed in detail. The Bear Creek Trunk Sewer in Surrey, BC, Canada is a 2845 m long, 600 mm to 900 mm diameter reinforced concrete and asbestos cement line. The pipe was installed in 1972. There are known corrosion, erosion, sedimentation, and odor issues. The objective of the PPR survey was to determine the condition and remaining service life of this by mapping its wall thickness, rebar cover and detecting voids and/or other anomalies within or outside the pipe wall. PPR results confirmed minimal corrosion at the crown and 95 mm to 97 mm remaining wall thickness with little variation over the inspected length. Rebar cover appeared to be sufficient with no void type anomalies on any of the inspected lines.

A 120 inch diameter brick lined combined sewer pipe was inspected with PPR in Portland, Oregon. The Taggart Outfall pipe was built in 1906 and experienced wet weather overflows. In order to design the most appropriate rehabilitation strategy the knowledge of voids outside the sewer was critical. Over 6,000 ft of high resolution line data were collected via manned entry. Due to the highly complex nature of the geophysical data, data processing and interpretation was a critical component of this project. PPR data revealed voids both outside and within the pipe wall and thus provided engineers the information needed to take the appropriate approach to rehabilitate the pipe.

With limited available funding and budget constraints becoming more prevalent, timing of rehabilitation and overall intelligent asset management is more critical than ever. PPR provides engineers and utility owners the information to accurately estimate the remaining life left in a pipeline, refine timing of repairs, and ultimately better allocate funding for asset management.

2. INTRODUCTION

Pipe penetrating radar (PPR), the in-pipe application of ground penetrating radar (GPR) is one of the most promising quantitative pipe condition assessment technologies to emerge in recent years. With most of the underground pipe infrastructure reaching the end of their design life there is a need to provide measurable data in order to establish the extent of rehabilitation required or the timing of replacement for large diameter critical pipe lines.

Although Closed Circuit Television (CCTV) inspection methods are effective and widely available tools for identifying visible defects on the internal wall of pipes, CCTV cannot see behind the pipe's inner surface, nor can it quantitatively determine the extent of corrosion. PPR technology allows the implementation of proactive preventative maintenance procedures for non-ferrous wastewater and water underground infrastructure. The combined application of PPR, CCTV and LiDAR provides the most complete and state of the art inspection technology to enable proactive asset management and allow utility owners to plan and schedule the inspection and rehabilitation of critical utilities prior to the occurrence of emergency scenarios.

This paper highlights the benefits of using PPR. Examples to illustrate the key benefits are drawn from two projects, one conducted with a robotic platform the other via manned entry.

3. OVERVIEW OF PPR IMAGING TECHNIQUE

Ground penetrating radar is the general term applied to techniques that employ radio waves to profile structures and features in the subsurface. Pipe penetrating radar (PPR) is the in-pipe application of GPR.

Signal penetration depth is dependent on the dielectric properties of the pipe and the host material, and on the antenna frequency. Detectability of targets in the ground depends on their size, shape and orientation relative to the antennas, contrast with the host medium as well as external radio frequency noise and interferences. The penetration depth of high frequency antennas (1.0 GHz to 2.6 GHz) which are the most suitable for pipe investigations is on the order of 1 ft to 5 ft beyond the pipe wall, depending on the material of the pipe inspected. PPR can be used to detect pipe wall fractures, changes in material, reinforcement location and placement, and pipe wall thickness. 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.

The recorded raw data is processed in order to enhance anomalies at deeper levels. Frequency filtering is used to remove noise. SewerVUE’s proprietary RadART software package was used for applying different correction, gain and filter functions. The interpretation is then superimposed on the processed PPR profiles (Figure 1).

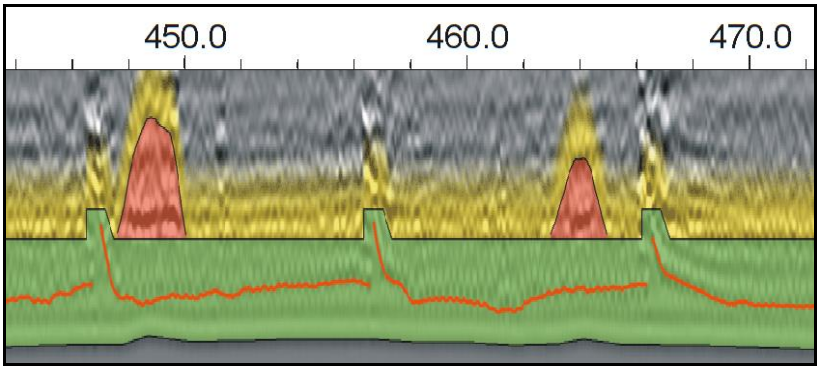

Figure 1. Robotic PPR data is displayed with the interpretation overlaid.

4. SURVEY EQUIPMENT

The SewerVUE Surveyor is the first commercially available multi sensor inspection (MSI) robot that uses visual and quantitative technologies (CCTV, LIDAR, and PPR) to inspect underground pipes (Figure 2). This fourth generation PPR pipe inspection system is mounted on a rubber tracked robot and equipped with two high-frequency PPR antennae. The system used in Surrey, BC, Canada can be adjusted for 21 to 60-inch diameter pipes, the PPR 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 and locating voids outside the pipe. CCTV data is recorded simultaneously and is used for correlation with PPR data collection.

Figure 2. The fourth generation SewerVUE Surveyor multi sensor inspection robot equipped with HD pan tilt zoom CCTV, PPR and LIDAR.

The sensors mounted on the robot take quantitative measurements of inside pipe walls. LIDAR technology employs a scanning 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.

5. CASE STUDY #1: Bear Creek Trunk line, Surrey, BC, Canada

The City of Surrey (City), BC, Canada owns and manages a network of sanitary sewers. It is of interest to the City to measure the rate of deterioration and the structural condition of its sewers, especially the large diameter (>600 mm) ones. It is of particular interest to know the remaining service life of these critical assets. A catastrophic failure would cause service disruption, serious environmental damage such as sanitary sewer overflows (SSO) and would be very costly to repair. A too early rehabilitation or replacement on the other hand, would be a wasteful use of limited resources.

Concrete sewers are prone to deterioration due to H2S corrosion. This toxic gas aggressively attacks and corrodes concrete and over time gradually eats away the pipe, the damage being most severe at the crown. Standard inspection methods such as CCTV are unable to detect the amount and rate of corrosion. The age of the pipe (a common proxy used for timing of rehabilitation) is also of limited use, an old pipe can still be in an excellent structural condition, while a new one can experience failure due to excess H2S corrosion or material or installation defects. (One of our recent projects involved the inspection of 20,000 ft of sewer pipe that was only seven years old and already experienced structural failure.)

The Bear Creek Trunk line is a 2845 m long concrete and asbestos cement pipe that was installed in 1972. Bear Creek has eroded to the pipe and there are known corrosion, erosion, sedimentation, and odor issues. The pipe has never been inspected during its 43 year service life. The City commissioned to conduct a high-frequency pipe penetrating radar (PPR) survey to inspect sections of the Bear Creek Trunk Sewer. The objective of the PPR survey was to determine the condition and remaining service life of this critical pipe by mapping its wall thickness, rebar cover and detecting voids and/or other anomalies within or outside the pipe wall.

Figure 3. Technicians preparing for deployment of the SewerVUE Surveyor at the Bear Creek Trunk Sewer in Surrey, BC, Canada.

This project's PPR survey was completed using 2.3 GHz frequency antennae while the pipe remained in service. Narrow manhole frames, offset manholes and high flow conditions created deployment challenges. Most of the work was completed during night shifts.

2D line data were collected on the crown of the pipe. The 2.3GHz antenna frequency provided good quality data and signal penetration to allow analysis to a depth of 20 to 30 centimeters from the inside pipe wall surface (Figure 4).

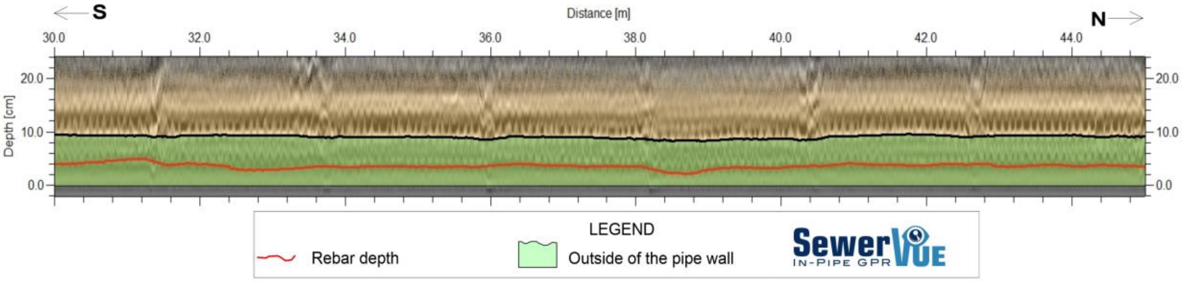

Figure 4. "Classic view" PPR results for the Bear Creek Interceptor, Surrey, BC.

PPR inspection results are summarized on distance (meter) vs. pipe wall thickness and rebar cover (centimeters) graphs which are readily understood and are faster to review by lay audience (Figure 5). These summary graphs are based on data extracted from the processed and interpreted individual PPR depth sections. The distance shown on each profile is measured from the center of the manhole of deployment. Pipe wall thickness is represented by a continuous green line. Change in rebar cover is represented by bar graphs showing rebar cover variations (min-max) for every 3 m interval. Red dots mark average rebar cover for the same 3 m interval.

In Phase 1 of the project 388 m of PPR data were collected for the Bear Creek Trunk Sewer with the multi-sensor SewerVUE Surveyor inspection robot. Wall thickness was interpreted to be in the 80 to 100 mm range with little variation over the inspected length. Average rebar cover appears to be in the 3.5 – 5cm range with a few local higher deviations. There appears to be an anomaly between 54.7 and 55.6 m on Line 2 (Figure 4). The anomaly can be caused by possible ground disturbance or variations in the physical properties of the soil behind the pipe wall.

Preliminary results at the conclusion of Phase 1 concluded no significant structural issues on the inspected sections of the pipe.

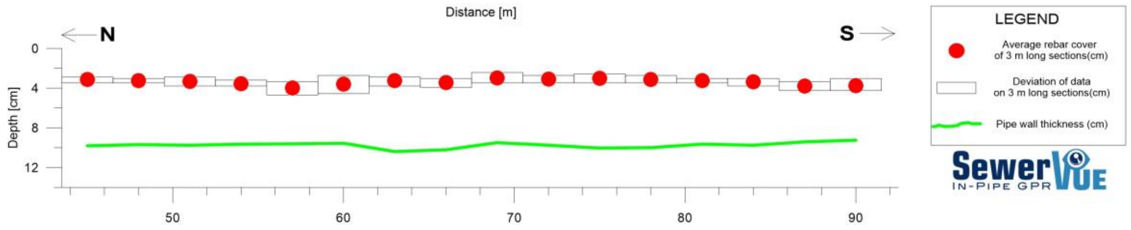

Figure 5. “Summary view” PPR results for the Bear Creek Interceptor, Surrey, BC Pipe wall thickness is represented by a continuous green line. Change in rebar cover is represented by bar graphs showing rebar cover variations (min-max) for every three metre interval. Red dots mark average rebar cover for the same three metre interval.

6. CASE STUDY #2: PPR Inspection of a 120 inch diameter brick lined sewer in Portland, Oregon

The second case study took place in a 120 inch diameter brick lined sewer that was originally constructed in 1906 (Figure 6). The Taggart Outfall is a combined sewer that, during intensive rainfall events, fills to capacity, and conveys flows to a deep tunnel system and can also convey wet weather overflows to receiving waters.

All pipe materials and structural members deteriorate with age and exposure to corrosive agents such as H2S. However, in most cases, damages cannot be detected by visual inspection. Hence, the application of non-destructive testing methodologies are increasing in condition assessment and further repair and rehabilitation, their information being crucial in the structural evaluation. Understanding the interior of the structures is the first stage to evaluate their state and to design potential repairs.

Bricks were commonly used liners for large diameter sewers in the late nineteenths and early twentieth century. However, it is difficult to obtain accurate information about their inner structure. Non-destructive testing (NDT) methodologies such as PPR provide a unique insight into the hidden structure of these pipes.

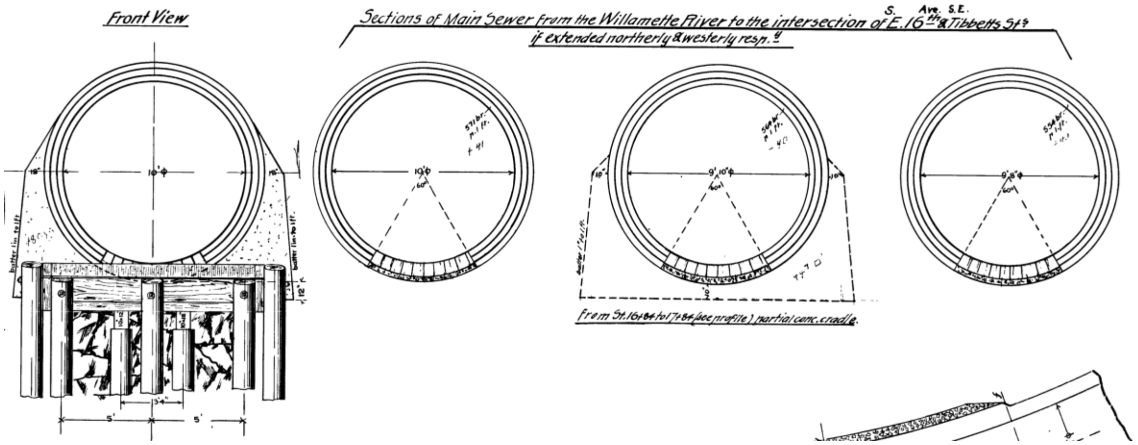

Figure 6. There was relatively little information available about the construction methods for the combined outfall.

In order to better inform the project team design on appropriate rehabilitation strategies, the knowledge of voids outside the sewer was important to rehabilitation methodology criteria. The engineering firm tasked with the design of rehabilitation commissioned SewerVUE to perform a non-destructive condition assessments before determining repair locations and methods. The primary purpose of the condition assessment was to locate and identify voids that may exist behind the brick lined pipe wall. This case study presents the methodology and results of the survey.

PPR instrumentation and field survey design

The inspection work was scheduled for the dry season for safety reasons and was completed in October 2014 (Figure 7). A total of 2040 feet were inspected via manned entry. The inspection was limited to pipe penetrating radar (PPR) data collection at the 12, 9 and 3 o'clock positions.

The PPR survey was completed using a 1 GHz hand-held antenna system. This antenna frequency provided the optimal trade-off between penetration and resolution and proved to be the most suitable in similar previous projects.

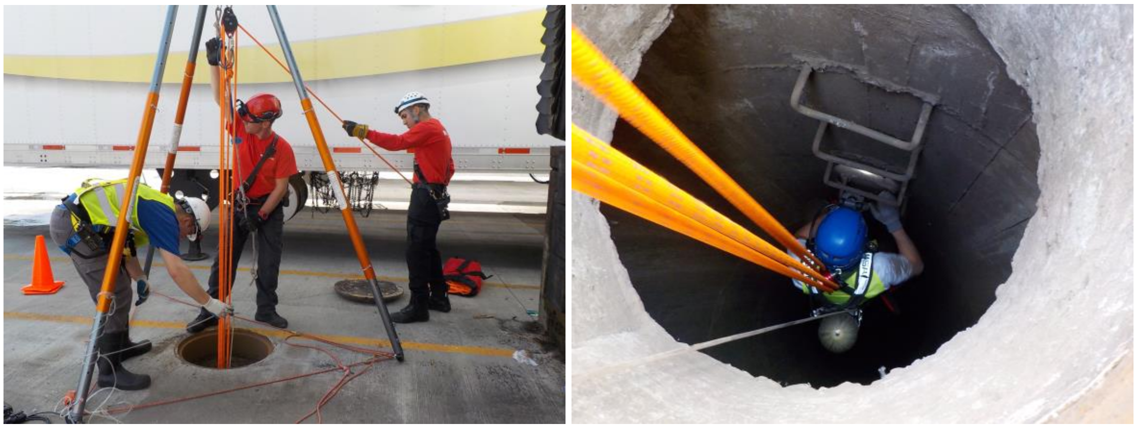

Figure 7. PPR technician and emergency rescue team supervisor preparing for the manned entry survey.

The PPR antenna was placed on a custom made extension arm to ensure good antenna/pipe wall coupling. Since the 12 o'clock position was the most critical these lines were surveyed twice, generally in 50 ft increments. The 3 and 9 o'clock positions were surveyed once in 100 ft long sections. At the end of every (50 or 100 ft) line the data were saved and the file name was recorded. Observations during the survey were recorded in order to aid data interpretation (Figure 8).

Figure 8. Visual observations such as infiltration or clay deposition were recorded during the inspection. Most of the pipe visually appeared to be in a good condition.

The PPR profiles have a depth scale in inches on the vertical axis, corresponding to about a 50 inches total depth of investigation (Figure 9). All the collected PPR data are of high quality and rich in detail.

PPR data interpretation

The overlapping arrangement of bricks created complex signal reflection and refraction patterns, thus data processing and interpretation proved particularly challenging. The main difficulty of PPR surveys lies in the interpretation of complex structures such as brick lined pipes. Irregular brick arrangement, the existence of different materials and objects generated numerous anomalies.

The interpretation was based on the careful analysis of certain reflections that show the expected brick liner/fill interface in all of the depth slices in all directions. A given reflection was compared to the surrounding signal strength. A processed and interpreted depth profile is shown in Figure 9.

The primary objective of the inspection was to identify voids larger than two inches in diameter outside the three courses of bricks. Voids were characterized according to size: 2-12 inches, 12-36 inches and >36 inches. No voids larger than 36 inches in size have been identified. In addition to identifying void type anomalies, other anomalies were also marked and interpreted. These include: non-void type anomalies outside the pipe, which were interpreted as metallic and wood objects. Voids and possible damage zone within the three courses of bricks were identified together with the interpreted brick + mortar and fill interface.

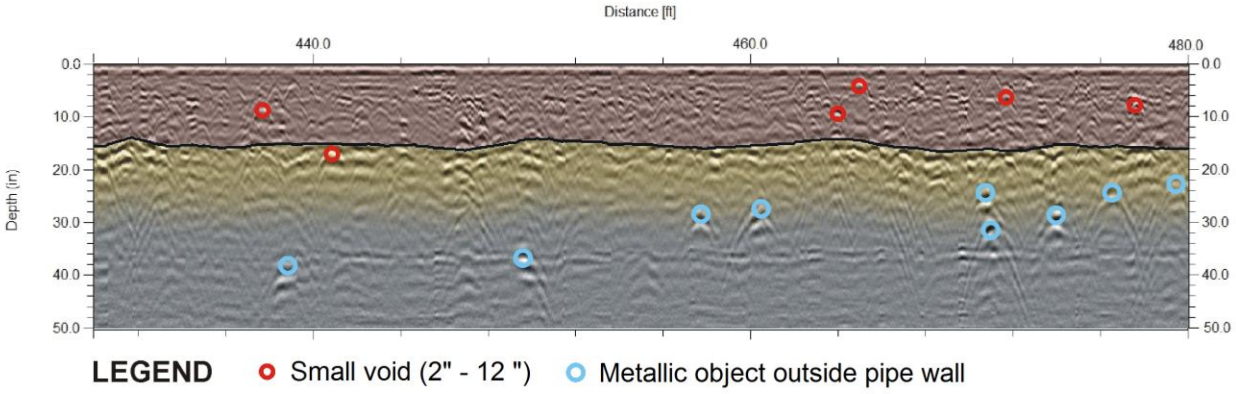

Figure 9. Interpreted PPR profile from a 120 inch diameter brick lined sewer.

Visible features such as laterals, infiltration, clay and Calcite deposits were noted (Figure 8) during the inspection. These notes were compared with the processed and interpreted PPR profiles. No direct correlation was found between the observed features and the interpreted profiles. This finding is significant and shows that “what you see is not what you get”, i.e. visible anomalies don’t accurately reflect the condition of the pipe.

PPR results

The interpreted anomalies were recorded on the processed PPR profiles and cross referenced with clock position and survey distance features. Areas of void type reflections are sometimes seen along the liner-fill interface (Figure 9). These zones are conspicuous by their pronounced irregular “bright spot” anomalies with higher amplitude and lower frequency (i.e. wider banding) relative to their surroundings. Void type anomalies were divided into three groups: small voids (2 -12 inch) medium voids (1 -3 feet) and voids larger than 3 feet. No voids larger than 3 feet were identified on any of the surveyed lines. The results are summarized and tabulated according to void size and location within the pipe (Table 1).

Table 1. Summary of the interpreted PPR anomalies for sections P2 and P3.

Survey	Clock position	Distance profiled (ft)	Nr of small voids in wall	Nr of small voids outside wall	Nr of medium voids inside wall	Nr of medium voids outside wall	Linear feet of possible damage zone (ft)
P2	12	800	58	19	0	2	5
	3	800	11	20	1	6	0
	9	800	5	4	0	1	0
P3	12	400	4	2	0	0	115
	3	300	7	3	0	1	0
	9	300	3	0	0	3	0

The three courses of bricks can be identified on some of the profiles some of the time (Figure 9). Well defined hyperbolic arches within the three courses of bricks were interpreted as small voids (Figure 9). Concentrated hyperbolic arch pattern indicate reflections and scattering from sides of individual bricks. This pattern may indicate missing mortar and these were identified as possible damaged zones.

Summary

A total 2040 ft of the sewer was surveyed with a hand held 1 GHz frequency PPR system. Signal penetration was between 20 to 40 inch depth, the data are of high quality. The most prominent feature on all the profiles is the pattern change often accompanied with a near horizontal, wavy interface at 16 ± 4 inch. This feature was interpreted as the brick liner/backfill interface (Figure 9). The observed anomalies were grouped into three categories in relation to this interface:

1) Anomalies within the three courses of bricks: well defined hyperbolic arches were interpreted as voids. A total of 220 small voids (2-12 in.) and 9 medium size (12-36 in.) voids were identified. A characteristic diffraction pattern from within the pipe wall was interpreted as pipe damage (e.g. missing mortar). 388 linear feet of possible pipe damage was found.

2) A total of 110 small (2-12 in.) and 27 medium size (12-36 in.) void type anomalies were found at the liner/fill interface. No voids larger than 36 inch were found on any of the surveyed clock positions.

3) Individual diffraction arches from within the fill (deeper than 18-20 in) most likely represent rocks, cobbles, boulders, timber and/or metallic construction debris and have no direct bearing on the structural condition of the pipe.

7. SUMMARY AND CONCLUSIONS

PPR has the unique ability to map pipe wall thickness and deterioration including voids outside the pipe, enabling accurate predictability of needed rehabilitation or the timing of replacement. Examples from a robotic and a manned entry project were used to illustrate how PPR can map remaining pipe wall thickness, rebar cover and voids outside the pipe.

The Bear Creek Trunk Sewer in Surrey, BC, Canada is a 2845 m long, 600 mm to 900 mm diameter reinforced concrete and asbestos cement line. The pipe was installed in 1972. There are known corrosion, erosion, sedimentation, and odor issues. The objective of the PPR survey was to determine the condition and remaining service life of this 43 years old RC pipe by mapping its wall thickness, rebar cover and detecting voids and/or other anomalies within or outside the pipe wall. Since the pipe had never been inspected, the owner was concerned about the condition and remaining service life of this critical asset. PPR results confirmed minimal corrosion at the crown and 95 mm to 97 mm remaining wall thickness with little variation over the inspected length. Rebar cover appeared to be sufficient with no void type anomalies on any of the inspected lines.

The 6,040 ft of high resolution PPR data from the 109 year old Taggart Outfall in Portland Oregon, a 120 inch diameter brick lined sewer revealed voids both outside and within the pipe wall and thus provided engineers the information needed to take the appropriate approach to rehabilitate the pipe.

With limited available funding and budget constraints becoming more prevalent, timing of rehabilitation and overall intelligent asset management is more critical than ever for municipalities and asset owners. Advanced pipe condition assessment technologies, including the SewerVUE PPR system, have demonstrated to be cost-effective, non-destructive methods that are able to help better refine structural condition and estimated remaining life of an interceptor, accurately determine overall severity of pipe degradation, as well as provide a basis for improved cost allocation and timing of rehabilitation efforts.