# Multi-Sensor Inspection: Assessing the Condition of Large Diameter Pipes with 3-D Digital Modelling

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## ABSTRACT

For the inspection of large diameter pipes, particularly wastewater and stormwater systems, CCTV is the commonly chosen inspection method. However, the long-term management of critical pipe infrastructure requires intelligent decisions made with detailed and quantitative data that CCTV cannot provide. With newly developed multi-sensor inspection (MSI) technologies, it is now possible to quantify the shape and size of pipes, and defects within them, in 3 dimensions. Advancements in MSI methods allow for measurement of remaining wall thickness, detection of voids developing outside the pipe, and the creation of 3-D digital point clouds with millimeter accuracy. By using these quantifiable measurements, a more accurate assessment of large water, wastewater and stormwater pipes can be obtained, allowing the pipeline owner to accurately estimate remaining service life via these predictive models.

Advancements in MSI technologies are highlighted in this paper, including 3-D LiDAR, sonar, and pipe penetrating radar (PPR), and how to combine these technologies to collect comprehensive, quantitative data from large diameter pipes. Benefits of the technology will be demonstrated by recent case studies.

The owner of a large, critical and irregularly-shaped sewer tunnel in Denver, Colorado needed accurate dimensions in order to undertake the needed rehabilitation. The 7,580 ft long tunnel was inspected using multiple LiDAR devices, sonar, and a high-definition 360-degree CCTV camera deployed on a custom-built long-range inspection platform. This combination of sensors provided a detailed, accurate and comprehensive report that was critical for an effective rehabilitation plan.

The second case study illustrates how Melbourne, Australia, used a robotic, multi-sensor crawler to inspect critical sewer lines in the 23.5-to-37.5-inch range. These reinforced concrete pipes were inspected with pipe penetrating radar, LiDAR, and high-definition CCTV camera in order to design an effective asset management plan.

The effectiveness, adaptability and affordability of the described technologies allow asset managers to obtain comprehensive and actionable data that in turn are essential for effective asset management.

## INTRODUCTION

For municipalities and contractors in a limited budget environment, it is very important to keep costs as low as possible. Efficient asset management is a key part of this goal. Especially when it comes to water and wastewater infrastructure, creating effective asset management plans can be challenging. Traditional pipeline condition assessment methods often do not deliver accurate data for asset managers to make the right decision. On these occasions is where modern techniques become very useful as the Multi-Sensor Inspection (MSI). Utility owners can develop predictive models of the remaining useful life of their assets by collecting comprehensive, quantitative data from pipelines. Making use of this model, pipes can be replaced at the right time, before they fail but without the wasted cost of replacing them too early. Preventing the cost incurred by catastrophic failures, as well as the wastefulness of replacing pipes that still have decades of useful life remaining to them, budgets can be pushed much further.

Using more than one type of survey method may be required to collect comprehensive data required to build a useful predictive model. The two case studies presented in this paper by Multi-sensor inspection methods were employed to gather quantitative pipeline condition data. LiDAR, Sonar, Pipe Penetrating Radar (PPR) and CCTV were the methods used in these case studies.

The owner of a critical, large diameter pipe in Denver, Colorado, was facing a similar problem where limited information about the condition of the pipe was known. The tunnel in question was in poor condition and needed rehabilitation. Sliplining was the chosen method, however, due to the tunnel's length and irregularity there were complications in designing the liner. A multi-sensor inspection using LiDAR and sonar was commissioned in order to collect the needed geometric information.

On the other side of the world, in Melbourne, Australia, another pipe owner needed quantitative data about the condition of their pipes. In this case, the utility owner had very little information about the current condition of the lines. Following the PPR survey, they could make informed decisions about which of the lines needed immediate attention, and which lines could afford to have maintenance deferred to a later date.

## THE TECHNOLOGY

LiDAR, is a technique used for geometric pipeline condition assessment. LiDAR profiling can bring together very precise measurements of a number of parameters, including ovality, deformations, lateral size, offset joins, and flow level. The LiDAR technology works by projecting a laser and measuring the time it takes for the laser to reflect off a target and return to the point of projection. "Time-of-flight" can provide a highly precise measurement of distance, this means the length of time that elapses between emission of the light signal and that signal reaching its target (Salik & Conow, 2012). LiDAR pipe scanning technology collects 2-D cross sections of the pipe wall continuously (Figure 1). A high-resolution 3-D model of the pipe can be created by compiling these cross sections. Outputs from LiDAR surveys can vary quite widely even when the same profiler is used. Engineers and utility owners must take care to assess the accuracy and calibration of the systems, as well as the repeatability of the results (Travis & Shelton, 2012).

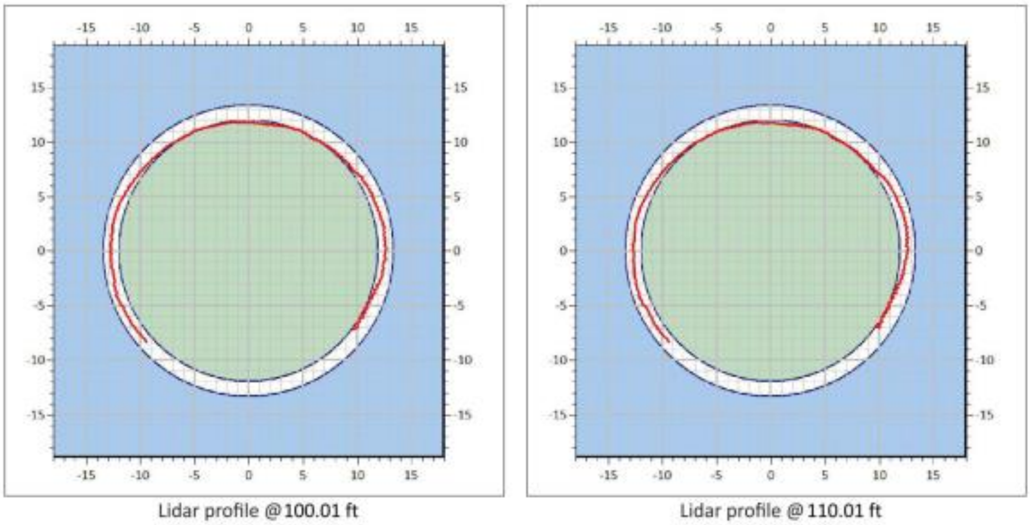


**Figure 1. Example of LiDAR cross-sections.**

Pipe penetrating radar is the application of high-frequency radar pulses from within a pipe to assess the condition of the pipe wall. PPR is similar to GPR, though it utilizes only high-frequency antennae. PPR can see through the pipe's inner wall, measuring wall thickness, as well as rebar cover in reinforced concrete pipes (Figure 2). PPR can also detect voids in the soil outside the pipe wall, while those voids are still relatively small (Ékes, et al., 2011). PPR is effective in any non-ferrous pipe (RCP, AC, RP, PVC, HDPE, etc.).

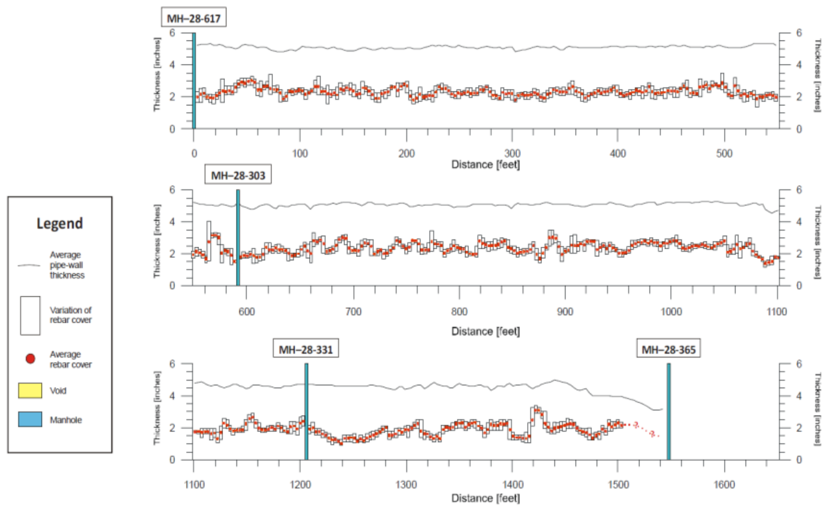


**Figure 2. Summarized PPR results. Pipe wall thickness is represented by a continuous black line. Change in rebar cover is represented by bar graphs showing rebar cover variations (min-max).**

In the two case studies presented in this paper, these sensors were deployed using two different platforms: a tracked ROV (Surveyor) and a float (MPIS). The ROV collected CCTV, LiDAR, and PPR data, while the float collected LiDAR, Sonar, and CCTV data. By using these different methods together on unmanned vehicles, a comprehensive set of data can be collected while avoiding any of the dangers and pitfalls of man entry operations.

## CASE STUDY #1: DENVER, CO

The owner of a reinforced concrete sewer tunnel located under a suburb of Denver knew the tunnel needed rehabilitation. However, they were facing a discrepancy between the realty of the tunnel and the original drawings. The tunnel was constructed over a period of 2 years in the late 1970’s. This tunnel was irregularly-sized, ranging from 70 to 80 inches in diameter. The tunnel was horseshoe-shaped, with the invert having a wide V shape. This differed somewhat from the as-built drawings (Figure 3). The pipeline was constructed first by excavating the tunnel. Then, steel ribs were placed throughout. This was followed by lining the tunnel with minimum six-inch thickness shotcrete. The invert was constructed from cast-in-place concrete, placed following completion of the shotcrete coating. The final phase was the installation of a coal-tar epoxy coating for protection.

The length of the inspection was 7,580 feet. Most of the line was between 50 and 90 feet underground, and the only available access points to the tunnel were a large portal at the upstream end, and a manhole at the downstream end.

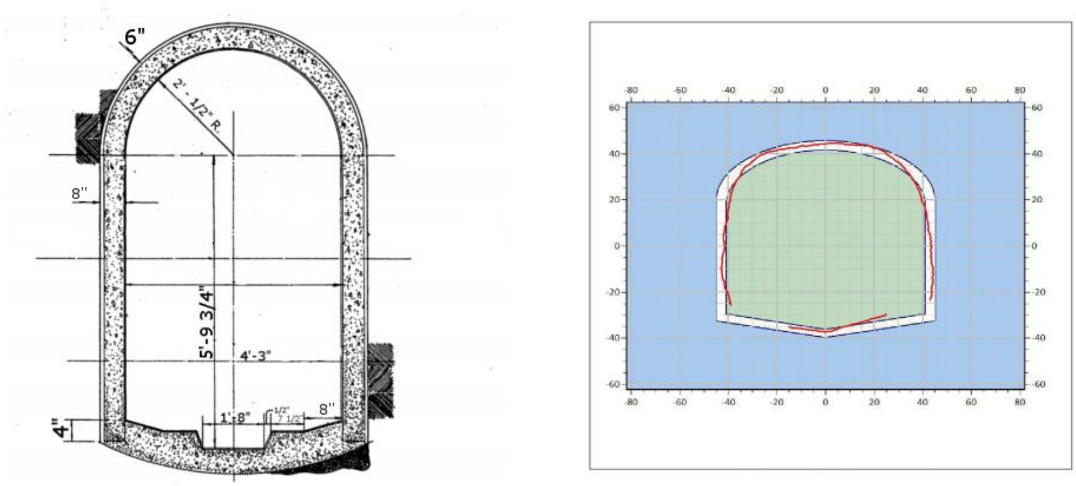


**Figure 3. The tunnel's as-built drawing (left) compared to the profile as measured by LiDAR and sonar (right).**

The primary intention of the inspection was to collect detailed geometric information necessary for designing a sliplining plan. The tunnel's irregular size and shape, as well as the lack of accessibility, made the rehabilitation project more complicated than usual.

A custom-built free-floating system was designed to perform the inspection. The tunnel's irregularity and length introduced further complications to the job. Taking it out of service for the inspection was not an option, and the flow was too high for a crawler to be useful; therefore, a float inspection was proposed. The typical equipment for a multi-sensor float inspection uses a float that is connected to the surface via a tether cable. However, the regular (3300 ft) tether length was not sufficient to inspect the entire 7,580 feet of tunnel. Even if the float was deployed from either end, there would still be a gap in the middle. The tether-less system carried all the necessary electronics on board, including two banks of batteries. It was estimated that the inspection would take 22 to 26 hours to complete, and it would not be possible to charge or replace the batteries during that time, so a dedicated power reserve was necessary.

The inspection began at the upstream end of the tunnel, with the float being deployed through the access portal. The system floated downstream, with the speed being controlled by an electric winch at the surface. Data collection proceeded over the course of 24 hours, with a pause overnight when flow levels dropped too low for the float to continue. Upon reaching the downstream manhole, a technician entered the tunnel to download the data collected by LiDAR, Sonar, and CCTV from the float before it was pulled back to the upstream access portal for extraction.

Analysis of the data revealed some notable features and anomalies within the pipe. 61.3 feet into the inspection, the pipe's dimensions decreased significantly and suddenly (Figure 4).

The first 61.3 feet measured 80 inches tall by 80 inches wide. After the change, the remainder of the pipe measured roughly 70 inches by 70 inches. There was a diameter variance throughout the length of the survey. In some sections, the diameter was reduced by as much as 5 inches, mostly coming from the crown being lower in those sections. Other sections showed outward bulges in the left or right wall, deflecting inward by as much as 5 inches. These irregularities are the result of the excavation method used to construct the tunnel.

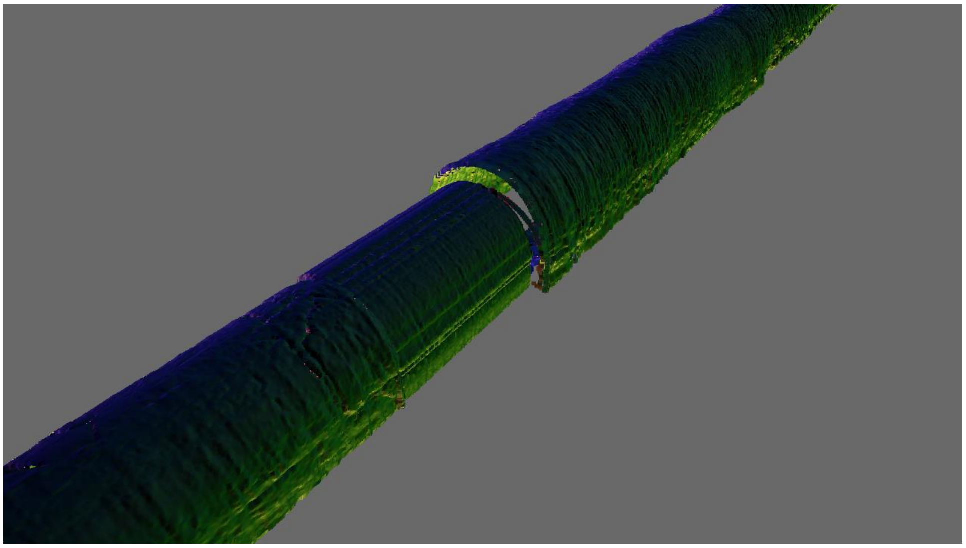

**Figure 4. 3-D model showing sudden diameter change.**

Throughout the survey, the coal-tar epoxy lining was seen to be delaminating and peeling away from the shotcrete beneath. Though this does not pose an imminent risk to the pipe's structure, it does illustrate the need for rehabilitating the pipe, as sections of exposed shotcrete will be more vulnerable to erosion and chemical attack. There were also localized instances of more significant damage or deterioration. These included sites where exposed shotcrete had begun to delaminate, (Figure 5) as well as a number of infiltration sites that were observed to be dripping and others where only stains were visible. There were calcium-like deposits observed throughout the survey, most notably in the form of long, root-like deposits growing from the crown of the pipe.

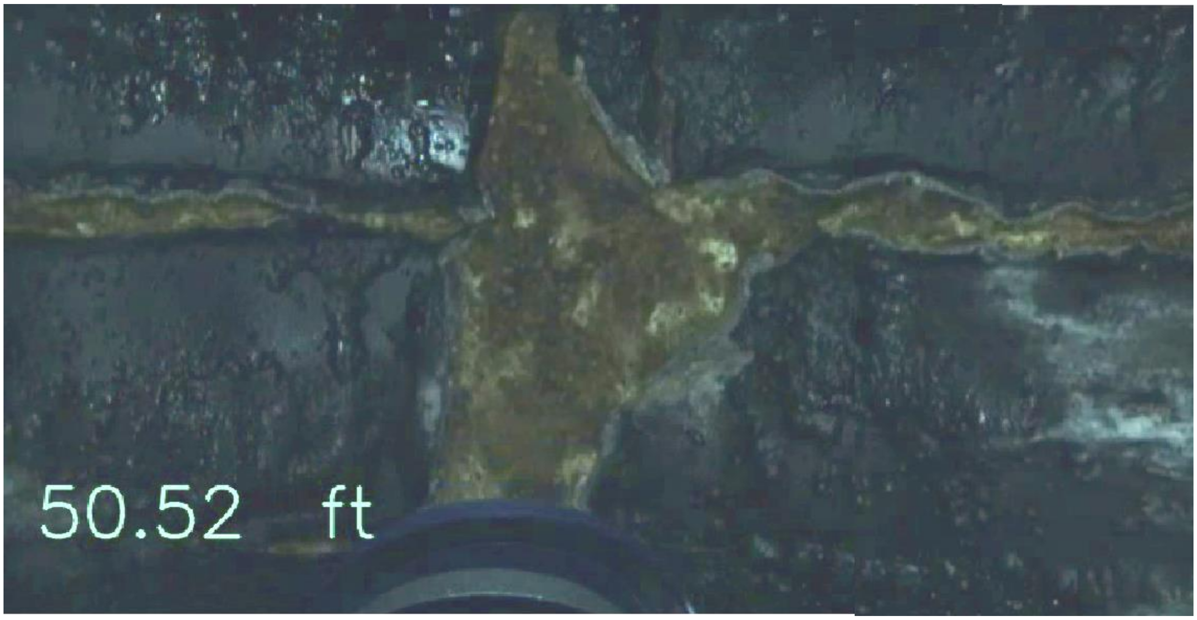


**Figure 5. CCTV image of the coal-tar epoxy lining peeling away from the shotcrete below. This image shows the crown of the pipe between the 10 o'clock and 2 o'clock positions.**

The data collected from this survey gave the owner the information necessary to design an effective rehabilitation plan. By knowing precise dimensions throughout the entire length, they could avoid the type of costly delays that may have occurred if irregularities were not discovered until rehabilitation had already begun. Multi-sensor inspections are useful for routine condition assessment, but are indispensable for cost-effective rehabilitation planning.

**CASE #2: MELBOURNE, AUSTRALIA**

In Melbourne, Australia, several lines of reinforced concrete pipe (RCP) were surveyed as part of a single condition assessment project. The client needed quantitative data about their pipes. The inspections were done using a tracked ROV, the 4$^{th}$ Generation SewerVUE Surveyor (Figure 6). The ROV was equipped with two PPR antennae, a LiDAR sensor, and a CCTV camera.

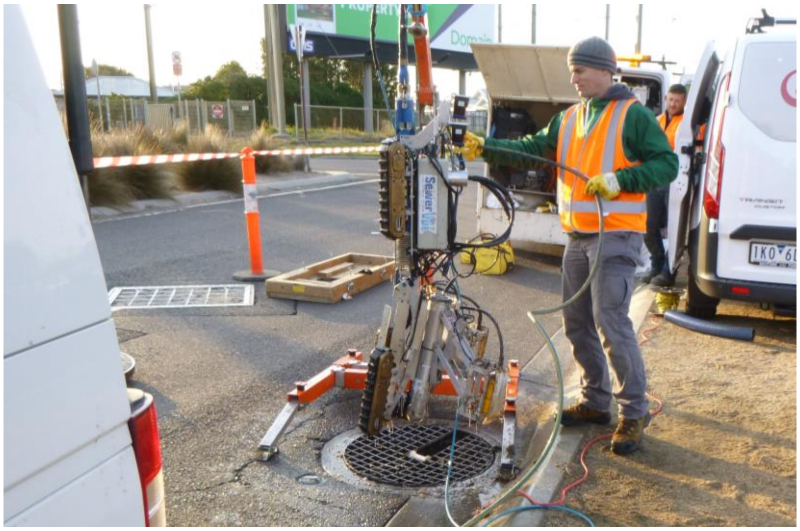

**Figure 6. The SewerVUE Surveyor at a deployment site in Melbourne.**

Mordialloc Main Sewer was the first section this survey looked at. This line was RCP with a diameter of 750 mm (30 inches). A 1297 m section was surveyed using a single deployment point near the middle of the section in question. LiDAR results from this section showed small but consistent deformation along the pipe's crown. The CCTV footage collected from this pipe showed a high degree of surface damage on the inner wall of the pipe. This damage appeared to be caused by chemical attack. Two significant points of structural damage were noted, including a small hole and circumferential fracturing located 33.4 m and 41.5 m downstream from the deployment point, respectively. The PPR data collected from the Mordialloc Main showed rebar cover that ranged from 35 mm to 60 mm deep. No significant voids or other anomalies were detected outside the wall of this pipe.

The Hobsons Bay Main comprised the second part of the survey. The Hobsons Bay Main is a 600 mm (24 inches) RCP sewer main. 572 m of this main was included in the scope of the survey. Starting from the access point and moving upstream, the LiDAR data from the survey showed the section between the deployment point and the next manhole to have increased wall loss compared to sections further upstream. This section was found to have significant sedimentation in it, and CCTV footage once again showed surface damage that appeared to be the result of chemical attack. PPR data showed rebar cover to be at least 15 mm throughout the length of the survey (Figure 7).

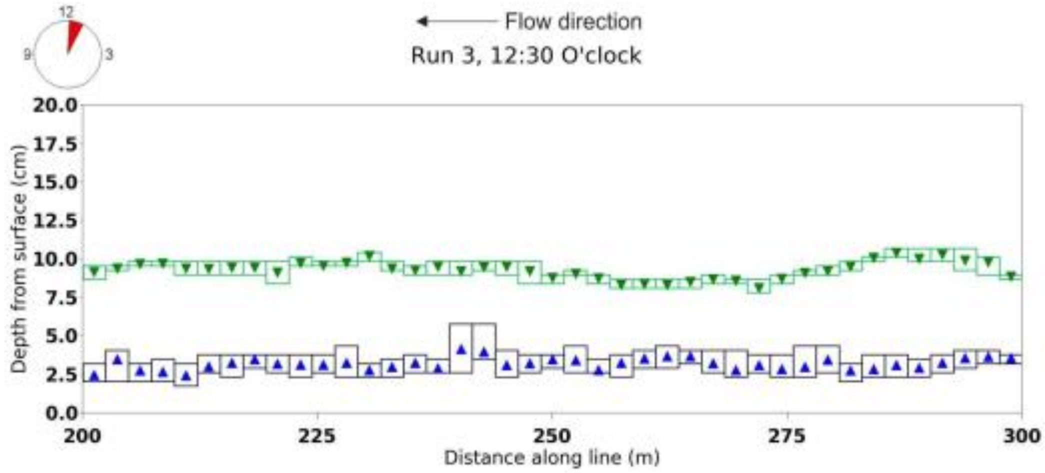


**Figure 7. Example PPR data from Hobson's Bay Main. Green triangles represent the average wall thickness of each 2.44 m section. Blue triangles represent average rebar cover.**

Third in the project was a survey of the Caulfield Intercepting Sewer, a 950 mm (37.5 inches) RCP line. An 1195 m section was surveyed using a single access point near the middle of the section. The sewer was found to be in generally good condition. Visuals collected by the CCTV camera showed only a few small defects mainly consisting of mild surface damage and localized staining along the crown of the pipe. LiDAR data showed minimal deformation of the pipe. However, it showed one section of pipe to be 1100 mm (43.3 inches) in diameter rather than the 950 mm (37.5 inches) that comprised the majority of the survey. From the PPR data, a large variance in rebar depth was observed throughout the survey. Rebar was not detected close to the wall surface, with the exception of one location near the access point.

The fourth and final line to be surveyed as part of this project was the Maribyrnong Main Sewer. This was a 760 mm (30 inches) diameter RCP line, and it was inspected from two different locations. This line was difficult to inspect due to significant sedimentation, and widespread attached deposits on the pipe walls. These deposits prevented the CCTV cameras from seeing the pipe walls in many areas. In areas that were free from deposits, significant surface damage was visible, and in some areas reinforcement could be seen. CCTV footage also revealed a hole in the pipe wall near one of the access points, as well as an intruding sealing ring. Due to the significant incrustation along the walls, LiDAR data collected from this line was not particularly insightful. The information collected by the PPR scanners showed little rebar cover along most of the inspected length. The section surveyed from the second access point showed improved rebar cover, but otherwise was in similar condition to the first section.

## SUMMARY AND CONCLUSION

In both case studies presented here, multi-sensor inspection technology was used to collect quantitative data about the conditions of the inspected pipelines. In the case of Melbourne pipes, the client received information showing which sections of the inspected pipes needed further attention, and which lines could potentially have maintenance deferred to a later time. The information also provided a baseline against which future tests could be measured, for the creation of an accurate model of the pipes' useful life. The inspection in Denver gave the client the sufficient information to put in place an effective rehabilitation plan.

The combination of CCTV, PPR, sonar, and LiDAR deployed on two different platforms provides an efficient solution to condition assessment. With limited budgets, utility owners can employ this approach to collect quantitative data about the condition of their assets. With this information, they can design predictive models that help them better allocate rehabilitation funds. Multi-sensor inspections are an effective, safe solution to pipe condition assessment.

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