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Trenchless Rehabilitation Planning and Design, Using Diagnostic Imaging, Condition Assessment and Multimodal Rehabilitation Techniques: A Case Study

Alex Palmer, Inversa Systems, Fredericton, New Brunswick
Stephen McCormick, Inversa Systems, Fredericton, New Brunswick
Daniel Madore, Via360, Montreal, Quebec

1. ABSTRACT

Across North America, roadway and drainage asset owners are facing a backlog of aging infrastructure whose deterioration rate is exceeding the ability and budget to replace it. (Venner, Marie. And Venner Consulting. 2014) Many owners are forced into a cycle of reactive, rather than proactive maintenance, repairing and replacing assets as they fail, rather than at the optimal time. This approach compromises safety and costs far more money, in both the short and long term, than a proactive asset integrity management approach. In an ideal world, asset owners would be able to replace all critical structures in advance of their design life, however this would exceed any realistic budget, be wasteful and socially disruptive. With advances in technology high quality non-disruptive condition assessment data is now available, which can be used to both optimize an individual asset's service life, in terms of safety and economics, and to form the basis for a long term highly effective asset integrity management program for the entire inventory.

This paper outlines how a single asset was identified, its condition assessed and a rehabilitation design using industry leading trenchless techniques was completed. The targeted audience are those interested in condition assessment and rehabilitation of buried infrastructure, specifically structures comprised of Corrugated Metal Pipe (CMP).

CMP is heavily reliant on supporting soil for structural integrity. A condition assessment must include an evaluation of the supporting soil to be considered complete. Previously there was no conclusive and quantifiable method to assess soil condition without damaging the pipe wall— further compromising the structural condition of the pipe. Backscatter Computed Tomography (BCT) has been applied to this unmet inspection challenge and is capable of providing diagnostic imaging to enhance the understanding of structural soil conditions around CMP assets. BCT allows a full structural condition assessment and is the only non-destructive method that is practical for imaging in-situ soil voids and undermining around CMP. (Allouche, Erez and Yang, Chenguang) As part of a comprehensive assessment protocol, this technology is used in asset management programs, rehabilitation planning, safe replacement or deferral and post construction QA/QC.

2. INTRODUCTION: CONDITION ASSESSMENT FUNDAMENTALS

Culvert washout, storm drain cave-in, road collapse, costly replacements, compromised safety and traffic disruption have been identified as common areas of concern for owners and managers of transportation, drainage and flood control systems comprised of CMP. Time and environmental conditions wear away the supporting soil around the pipe. Flow related undermining develops in the haunches and at the springline as water flows outside of the pipe and voids form in the roof and upper portions of the pipe as water flows from the road surface or embankment onto the pipe. As corrugated metal pipes are considered flexible conduits the structural integrity is dependent on the supporting soil. An improperly supported pipe will experience mechanical stress and deformation which can eventually result in a catastrophic failure. As a result, soil voids and undermining must be considered when evaluating the structural condition of the asset. (El Taher, M. and Moore, I.D. 2009)

Conventional pipe inspection methods are subjective and speculative, often lacking descriptive evidence of the condition of the pipe's supporting soil. Until now, testing methods have been limited to visual appraisals, acoustic assessment and destructive testing. A few experimental non-destructive methods that have been tested but have failed to yield reliable results include ground penetrating radar (GPR) and gamma-gamma logging. Visual appraisal, either in person or by remotely controlled CCTV, is effective in identifying corrosion, joint failure, misalignment, deformation and ovality. However, this method fails to provide information regarding the degree of soil loss in the supporting soil envelope of the CMP, potentially resulting in an overestimated or underestimated structural condition. Acoustic testing is done by striking the pipe and identifying anomalous regions by sound. This method is subject to frequent false positives due to soil compaction variability and soil composition, potentially resulting in a further underestimated structural condition. Destructive testing is conclusive, however it exacerbates potential soil void and corrosion problems by introducing avenues for soil ingress to the pipe. GPR can identify subsurface anomalous regions in certain materials, however, cannot measure through steel, making its use in CMP impossible.

Figure 1. Buried corrugated metal pipe under a highway used as a stream crossing.

The introduction of Backscatter Computed Tomography to CMP evaluation is the final conclusive step in full structural condition assessment. The end to end condition assessment protocol is suited to evaluate corrugated metal, plastic and composite pipe (lined or coated) of nominal diameters 900mm and larger. By employing a three-part condition assessment protocol, an accurate full structural analysis of the pipe is possible. In this context, a full condition assessment means that 100% of the pipe is evaluated and that all factors affecting the structural integrity of the installation are included in the assessment. These factors include the pipe's condition, the supporting soil structure, headwall condition, pipe and channel alignment, ovality, embankment and vegetation, among others. To achieve this, a three-part assessment protocol is employed which can be broken into two tiers of inspection. Tier 1 includes a rigorous visual assessment and an acoustic testing process which screens 100% of the pipe for anomalies. Tier 2 consists of BCT diagnostic imaging of the anomalous locations identified in Tier 1 to conclusively identify, visualize and quantify soil voids around CMP structures.

3. PROCEDURE: STRUCTURAL CONDITION ASSESSMENT OF CMP

3.1 Tier 1: Assessment and Screening

A visual appraisal is powered by a handheld tablet app and incorporates a forced ranking visual assessment with a photo collection process. A photo of the tablet app is seen in figure 2. The pipe and surrounding structure undergo a rigorous and repeatable 10-point visual inspection process which is a combination of the strongest aspects from over a dozen jurisdictions, including US Dept of Transportation (DOT), Federal Highway Safety Board, Ohio DOT, Alberta DOT, Ontario MOT, Arizona DOT, California DOT, New York State DOT, Oregon DOT, US Army Corps, and BC MOT. The visual features considered are (where applicable) Pavement, Guardrail, Headwall, Embankment, Pipe Alignment, Waterway Blockage, Scour, Cracks, Seams and Joints, Shape, Dents and

Figure 2. Tablet app in field use.

Localized Damage and Corrosion and Coatings. Each feature is rated on a scale of 1 through 5 with 1 being “as built” and 5 being “imminent failure”.

The acoustic assessment or “knock test” is done to determine the potential presence and location of suspected voids within the pipe and aids in prioritizing which anomalies to image. A detailed knock test is done by striking corrugations at 15-20cm increments on both sides of the pipe, at five relative elevations: waterline, pipe spring line, forty-five degrees above and below spring line and obvert. Based on the acoustic assessment, the suspected void regions are recorded for location and size.

Figure 3. Acoustic anomaly identification or “knock test”.

All information for each asset is displayed on a proportionally representative “overview pipe map”, shown in figure 4, representing each opposing wall of the pipe. This includes all visual indicators, acoustic anomalies and, in Tier 2, BCT image locations. To accommodate large lengths of pipes, the map is broken into “segment pipe maps”, as seen in figure 5, to allow for the display of all relevant features. In the example, the dark rectangles represent an acoustic anomaly on the pipe wall. The X coordinates indicate the distance from the inlet of the pipe section and the Y coordinates is measured as a clock position around the pipe barrel with the inspectors back at the inlet. Each corner of the rectangle is given its own pair of coordinates. The exact coordinates and reference points for all anomalies, visual indicators and BCT images are detailed in appendices within each report.

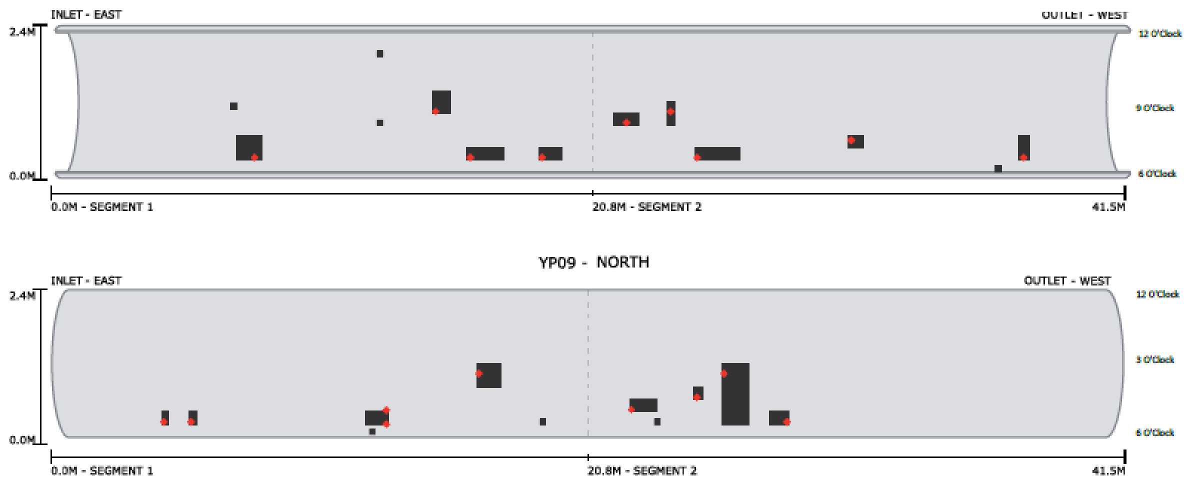


Figure 4. Overview pipe map displaying visual indicators as black squares, acoustic anomalies as black rectangles and BCT image locations as red diamonds.

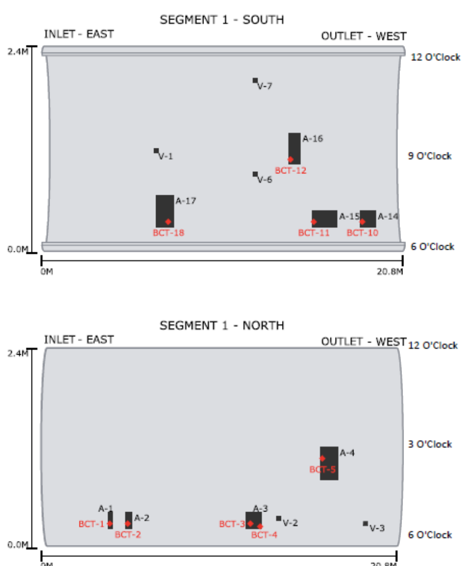


Figure 5. Segmented pipe map displays all pipe characteristics in greater detail with dimensions tabulated.

3.2 Tier 2: Backscatter Computed Tomography (BCT)

BCT is a form of industrial diagnostic imaging that provides information similar to that of a medical CT scan. Measurements are acquired with the field hardware and the information is transmitted for image reconstruction and report generation. Applied to CMP structures, BCT is able to image and distinguish between the CMP wall, supporting soil and void. The resulting image allows the verification of soil presence and/or void behind a CMP wall. Voids can be quantified and the geometry of the void visualized.

Using results from the visual and acoustic assessment, areas for diagnostic BCT imaging are selected. The BCT scanner is positioned against the pipe wall and a region of up to 30 cm per position is imaged and assessed. BCT images provide a cross sectional view behind the pipe wall. In the images the Y intercept indicates the front (accessible) side of the pipe wall. An increase in Y, indicates the depth behind the wall. The X axis is the range across the wall, where the image was taken. Figure 6 is a sample BCT image which shows a soil void along the CMP wall as well as "piping" going towards the top left corner of the image, indicating the direction from which water is washing away the supporting soil.

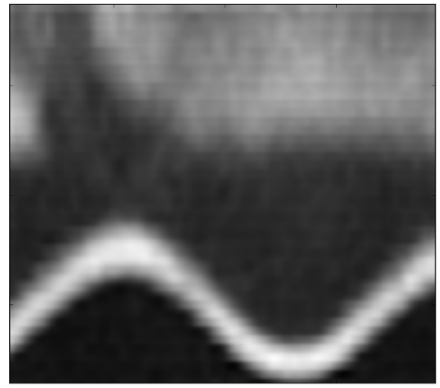


Figure 6. Sample BCT image which shows a soil void along the CMP wall as well as "piping" going towards the top left corner of the image, indicating the direction from which water is washing away the supporting soil.

These important pieces of information, along with visual indicators and position of void, allows the soil failure mode to be considered and the most appropriate remediation to be planned.

3.3 BCT Hardware consists of a scanner, a control tablet and an independent radiation isotope camera. Figure 7 shows the BCT hardware and a typical setup in a CMP structure. The tomographic image represents a relative density map of a two dimensional slice through a three dimensional image. Liability for the transportation and deployment of the radiation isotope is contracted to a third party provider, the isotope used is Iridium-192. This is commonly used in industrial radiography and is readily available.

Figure 7. Shows the BCT hardware being deployed in a CMP structure.

4. CASE STUDY: CITY OF LEVIS

The City of Levis, Quebec, Canada (City) owns and operates a significant storm water drainage system that serves the city and surrounding areas. Portions of this system are comprised of corrugated metal pipe. One section in particular is of high concern and was requested for immediate condition assessment to guide rehabilitation efforts. The asset is 180m in length and 2.4m diameter.

4.1.1 Condition Assessment Results A visual and acoustic assessment was carried out. Four acoustic anomalies were identified during the "knock test" of which two were chosen for follow-up BCT imaging. Only two locations chosen because the outlet section of pipe presented unsafe conditions for hardware deployment. The locations were measured from manhole access (STA0+000) to the outlet (STA0+180).

Figure 8. Overview pipe map displaying visual indicators as black squares, acoustic anomalies as black rectangles and BCT image locations as red diamonds.

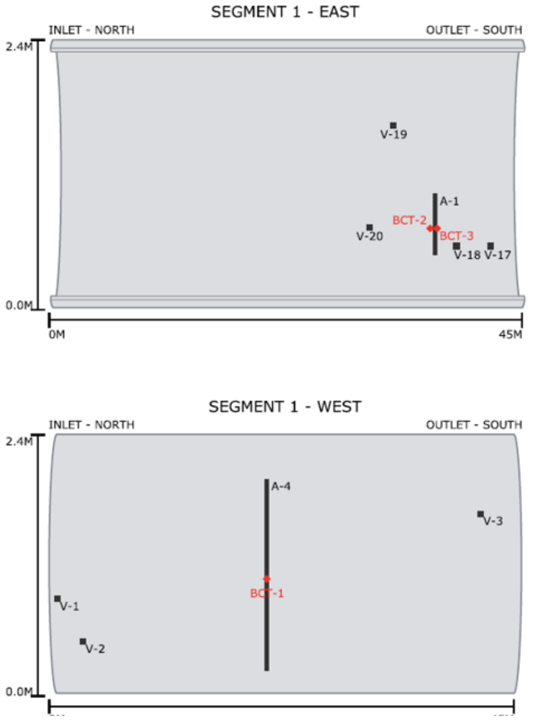
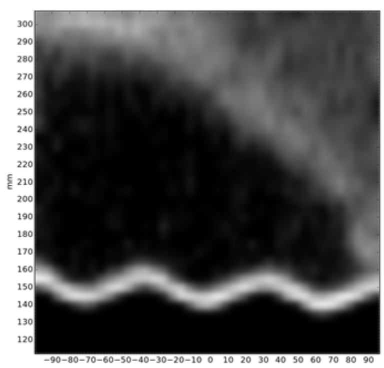


Figure 9. Segmented pipe map of pipe section 0m-45m.

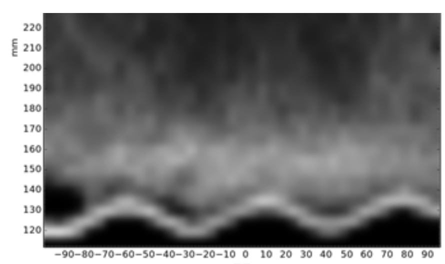
The visual inspection documented several deficiencies associated with the pipe barrel and the embankments. Most notably seams throughout the storm drain are in poor condition, several with visible voids both above and below the pipe, allowing water to run underneath causing flow related soil failure. The ovality of the pipe is greater than 10%, with the majority of issues being underneath Autoroute #73. Several rock impingements were noted, the largest of which was located directly beside the manhole entrance located beneath Autoroute #73, at (STA0+137). The bitumen coating throughout the pipe has become dried out and brittle, chipping during hammer testing. The outlet of the storm drain (STA0+156) to (STA0+180) is in very poor condition, two acoustic anomalies were found. Evidence of buckling and significant scour was noted. The outlet of the pipe is damaged with several large indentations.

4.1.2 Soil Verification with BCT Imaging

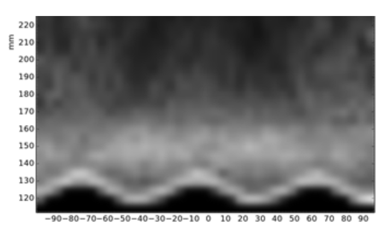
BCT images were taken at two locations to verify soil structure. The largest confirmed void was verified in image A-2141 and quantified to 14cm in depth spanning at least 3 corrugations. The location of this void was concerning due to its location directly under Autoroute #73. Image B-2142 displays discontinuous CMP wall, which was covered by a low density rubber seal, and a small soil void pocket behind a seam separation. Image C-2143 indicates a void in a single corrugation but it does not span corrugations. Image D-2144 confirms adequate backfill supporting this region of pipe



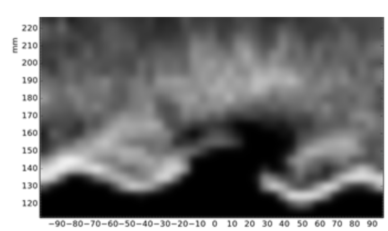
A-2141



C-2143



D-2144



B-2142

Figure 10. BCT images show various soil voids behind the pipe wall.

4.1.3 Condition Assessment Conclusion

The pipe is a relatively long structure and very different structural conditions exist over the length of it. As such it should be viewed in sections as there are unique implications due to the unique nature of the sections. Inspection of this asset began at Manhole #2 located on Avenue de la Rotonde, this is shown as (STA 0+000) with completion occurring at the outfall (STA 0+180).

Figure 11. Outlet of pipe.

The problems identified in the course of this work were primarily flow related issues. Soil voids and water inflow/outflow were consistently located near through-wall corrosion or joint/seam separations, this is typical of pipes in a deteriorated state and is consistent with flow related failure. Also, noted throughout the pipe was consistent deterioration of the bituminous corrosion coating on the pipe. Below the high water mark, this coating has been completely scoured away exposing the metal to corrosion and ultimately erosion failure. In the above high water mark areas of the pipe wall, this bituminous coating is also deteriorating, it was noted that this material is hard, prone to chipping and subject to impact damage. This coating is no longer performing as it was intended when originally installed.

The inlet section of pipe (STA 0+000 to STA 0+118) demonstrated repairable localized problems. Ovality measurements consistent with industry standards (CSA, AASHTO) were noted. This segment of the pipe shows almost uniform deterioration of the pipe invert caused by erosion. This was manifest in uniform corrosion along the invert, resulting in scaling. In over 95% of the corroded region, field measurements showed remaining wall thickness to support stability (>40%), however, this type of corrosion is subject to rapid failure due to erosion. In this segment of the pipe most of the joints show separation and deterioration.

The section of pipe including the segment under Autoroute #73 includes STA 0+118 to STA 0+156. As Autoroute #73 is subject to a high traffic volume, the risk to overall stability of this pipe is significantly greater under this section. During the course of this analysis, ovality measurements which exceed the accepted industry standards were noted in several locations. Most severe is the section of pipe at (STA 0+138) where a significant structural deficiency (impingement) was noted. This impingement is located close to the manhole access point under Autoroute #73 and is of high significance and must be monitored on a monthly basis. Ovality and protrusion measurements are recommended and any changes noted and brought to the attention of the asset manager immediately.

Figure 12. Map view of the pipe location and the infrastructure supported.

The outfall segment of pipe (STA 0+156 to STA 0+180) was installed at a severe downward slope, this section of pipe is not directly under Autoroute #73, but it does support the embankment and contribute to the Autoroute's stability. There are numerous and significant deficiencies noted in this segment, it is severely undermined and a highly visible wall buckling failure is occurring. It may be possible to temporarily stabilize this segment, but replacement is the only long-term viable solution, due to the advanced state of deterioration.

4.2.1 Rehabilitation Design Planning

A thorough review of the structural condition assessment of the storm water drainage section under Rotonde Avenue and Autoroute 73 in Levis Quebec was used to formulate a comprehensive rehabilitation plan. The main body of the pipe will be referred to in Stages 1, 2 and 3 of this project (STA 0+000 to STA o+156). The downward sloping outfall section was considered Stage 4 of this project (outfall).

Two primary rehabilitation techniques were identified as viable options for the rehabilitation of the pipe segment between STA 0+000 and STA 0+156): Spray in Place Pipe (SIPP) polymer solution and Centrifugally Cast Concrete Pipe (CCCP) solution.

Figure 13. The outlet of the CMP asset.

4.2.2 STAGE 1: CLEANING AND PREPERATION

To begin rehabilitation cleaning, sealing and void filling must be accomplished to achieve optimal results. This pipe was completely covered in a bituminous anti-corrosion coating. This coating was completely worn away in the invert of the pipe and deteriorated past the point of functionality elsewhere on the pipe wall. Removal was highly recommended and was a requirement for use of CCCP and SIPP.

4.2.3 STAGE 2: TUNNEL PLATE

A structural deficiency at STA 0+138 was identified. The nature and extent of this deficiency required localized repair beyond the scope of either CCCP or SIPP. This localized repair was addressed as a first action in Stage 2 prior to Stage 3 work. The deflection of the pipe at STA 0+138 represented a significant risk of pipe failure under Autoroute 73. It was recommended that a galvanized steel tunnel plate be used to reinforce and stabilize the pipe in this specific location. This technique offered the advantage of being assembled in the host pipe, as well as providing a localized repair strategy and excellent long term stability. The tunnel plate technique will cause some flow restriction, however it was an excellent trade off in risk mitigation and cost.

4.2.4 STAGE 3: PIPE BARREL REHABILITATION (LINING)

The main barrel of the pipe STA 0+000 to 0+156, was now considered prepared for lining. The two options were CCCP and spray in place pipe SIPP. Both options were detailed in the full report provided to the client with material properties, thicknesses, application method and curing specifications.

4.2.5 STAGE 4: DOWN SLOPING OUTFALL STABILIZATION

This section discusses the recommended action for the down sloping outfall section of the pipe from STA 0+156 to STA 0+180. This segment of the pipeline was in a state of advanced deterioration. There were obvious signs of undermining throughout the entire invert, wall buckling failure in the invert, and severe damage to the pipe end.
The long term viability of this segment was questionable, therefore replacement of this section was recommended.

Possible risk mitigation strategies can be undertaken to prolong the effective service of this segment of the pipeline. The invert of the outfall must be stabilized and soil stabilization will be of key importance to this effort. If the asset owner deems (maximum service life extension is a priority for this segment) a spray applied protective coating is highly recommended.

4.2.6 Rehabilitation Design Conclusion

The rehabilitation design described is based on the most robust possible non-destructive condition information available today. By ensuring that all factors effecting the assets structural condition are considered, a rehabilitation can be executed with a high degree of confidence. The service life extension represented by this design is similar to that of a newly installed structure and is all done without disrupting the provision of transportation service on the roadway.

5. INDUSTRY IMPLICATIONS OF STRUCTURAL CONDITION ASSESSMENT

CMP structures are subject to a variety of failure modes and each site presents unique conditions that impact the structural condition. By utilizing the best in condition assessment and combining the latest in trenchless techniques the most responsible, cost effective and safe solution can be applied to aging infrastructure. Many other soil voids have been identified during other projects across North America. These voids have presented unique geometry which offers valuable information to the state of the supporting soil which can be critical to designing an effective trenchless rehabilitation. The unique nature of each asset and the importance of identifying what sort of failure mode is present when planning and designing an effective rehabilitation is now able to be more completely understood. By addressing this pipe trenchlessly, as opposed to digging it up, significant cost savings will be achieved. Once the construction is complete the real construction costs will be reported.

By applying this condition assessment to large sections of inventory, Tier 1 screening can exclude structurally sound pipes from Tier 2 screening. Structurally sound pipes can then be monitored and deterioration trended over time. Assets that require further investigation into their structural condition undergo Tier 2 assessment for full asset diagnosis. This information not only optimizes individual rehabilitation projects, it optimizes the long-term asset management and rehabilitation planning of CMP assets. The information provided allows for the maintenance of assets to be either safely deferred or planned for future remediation activities.

6. LOGISTICS

Tier 1 assessment is typically conducted using a two-person team to conduct the visual appraisal and acoustic assessment. Lineal feet per day is dependent on site conditions however it can be expected that in one work day 340 meters of pipe can be completed. The interim or Tier 1 report is generated and consultation with the client can begin to prioritize and select assets for Tier 2 assessment within 3 days of completion.

Tier 2 assessment is also typically done with a two-person team plus the radiation isotope technician. It is typically estimated that 6-12 BCT scans can be completed per day, depending on site conditions and the distance between BCT locations. The full engineering report is completed within 14 days of the last field day.

Cost Items

- Tier 1 Assessment
    - Acoustic and visual assessment field work cost
    - Report generation
- Tier 2 Assessment
    - BCT deployment
    - Image reconstruction
    - Report generation
- Variable costs
    - Equipment mobilization and field team travel
    - Accommodation
    - Equipment rental
    - NDT radiation isotope service rental

Project Constraints Include:

- Access is dependent on weather and water levels
- Water in the pipes is at a level to allow for safe entry by the field team
- Site temperature is above -10 Celsius
- Inspection location is above waterline
- Man access is required
- Client to provide location of on-site testing in advance
- Inspection of catch basins in not included
- Client will be responsible for notifying all affected individuals of the proposed BCT imaging
- Trained Field Team will conduct the BCT imaging
- A local certified NDT subcontractor will be arranged to deploy the radiation source

7. CONCLUSIONS

A full understanding of the structural condition of an asset requires information about all relevant factors affecting that structure. By achieving this, through robust condition assessment, the most effective strategy can be formulated to extend the service life of an asset as long as possible at the lowest possible cost. Condition assessment is a key part of the value chain associated with good asset management practice which allows proactive maintenance and rehabilitation to be undertaken before structural issues render many options impractical.

In this paper, the value of robust condition assessment has been displayed and the benefits realized as the asset has been moved through the asset management value chain. This chain begins with inventorying and prioritization and ends with rehabilitation planning and ultimately rehabilitation and continued operation without any service disruption.

Fundamentally, good asset management practices that are predicated on robust information allow infrastructure owners and operators to increase service uptime, decrease spending and maximize safety.

8. REFERENCES

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