AECOM Imagine it. Delivered.

City of London

Interim Asset Management Strategy: Arva Pumping Station to Huron Street Water Transmission Main Municipal Class Environmental Assessment Master Plan London, Ontario

Prepared by:
AECOM Canada Ltd.
410 – 250 York Street, Citi Plaza
London, ON   N6A 6K2
Canada

T: 519 673 0510
F: 519 673 5975
www.aecom.com

Prepared for:
The Corporation of the City of London
300 Dufferin Avenue
519-661 2489

Date: October 2020

Project #: 60619503

Distribution List

# Hard Copies	PDF Required	Association / Company Name
1	✓	City of London
1	✓	AECOM Canada Ltd.

Revision History

Rev #	Date	Revised By:	Revision Description
0	September 28, 2020	Khalid Kaddoura Chris Martire	Draft report revised
1	October 26, 2020	Khalid Kaddoura	Final report revised

AECOM Canada Ltd.
410 – 250 York Street, Citi Plaza
London, ON N6A 6K2
Canada

T: 519 673 0510
F: 519 673 5975
www.aecom.com

Stephen Romano, P.Eng.
Environmental Service Engineer - Project Manager
The Corporation of the City of London
300 Dufferin Avenue
519-661-2489

October 26, 2020

Project #
60619503

Dear Mr. Romano;

Subject: Interim Asset Management Strategy: Arva Pumping Station to Huron Street Water Transmission Main Municipal Class Environmental Assessment Master Plan London, Ontario

AECOM is pleased to submit the final report entitled "Interim Asset Management Strategy".

In case you have any questions, please contact the undersigned for more details.

Sincerely,
AECOM Canada Ltd.

Khalid Kaddoura, PhD, P.Eng., PMP, ENV SP, CLSSBB
Project Manager/Asset Management Specialist, Water
khalid.kaddoura@aecom.com

John Hassan, PMP, CET
Senior Vice President
John.hassan@aecom.com

KK:cm
Encl.
cc:

Statement of Qualifications and Limitations

The attached Report (the "Report") has been prepared by AECOM Canada Ltd. ("AECOM") for the benefit of the Client ("Client") in accordance with the agreement between AECOM and Client, including the scope of work detailed therein (the "Agreement").

The information, data, recommendations and conclusions contained in the Report (collectively, the "Information"):

- is subject to the scope, schedule, and other constraints and limitations in the Agreement and the qualifications contained in the Report (the "Limitations");
- represents AECOM's professional judgement in light of the Limitations and industry standards for the preparation of similar reports;
- may be based on information provided to AECOM which has not been independently verified;
- has not been updated since the date of issuance of the Report and its accuracy is limited to the time period and circumstances in which it was collected, processed, made or issued;
- must be read as a whole and sections thereof should not be read out of such context;
- was prepared for the specific purposes described in the Report and the Agreement; and
- in the case of subsurface, environmental or geotechnical conditions, may be based on limited testing and on the assumption that such conditions are uniform and not variable either geographically or over time.

AECOM shall be entitled to rely upon the accuracy and completeness of information that was provided to it and has no obligation to update such information. AECOM accepts no responsibility for any events or circumstances that may have occurred since the date on which the Report was prepared and, in the case of subsurface, environmental or geotechnical conditions, is not responsible for any variability in such conditions, geographically or over time.

AECOM agrees that the Report represents its professional judgement as described above and that the Information has been prepared for the specific purpose and use described in the Report and the Agreement, but AECOM makes no other representations, or any guarantees or warranties whatsoever, whether express or implied, with respect to the Report, the Information or any part thereof.

Without in any way limiting the generality of the foregoing, any estimates or opinions regarding probable construction costs or construction schedule provided by AECOM represent AECOM's professional judgement in light of its experience and the knowledge and information available to it at the time of preparation. Since AECOM has no control over market or economic conditions, prices for construction labour, equipment or materials or bidding procedures, AECOM, its directors, officers and employees are not able to, nor do they, make any representations, warranties or guarantees whatsoever, whether express or implied, with respect to such estimates or opinions, or their variance from actual construction costs or schedules, and accept no responsibility for any loss or damage arising therefrom or in any way related thereto. Persons relying on such estimates or opinions do so at their own risk.

Except (1) as agreed to in writing by AECOM and Client; (2) as required by-law; or (3) to the extent used by governmental reviewing agencies for the purpose of obtaining permits or approvals, the Report and the Information may be used and relied upon only by Client.

AECOM accepts no responsibility, and denies any liability whatsoever, to parties other than Client who may obtain access to the Report or the Information for any injury, loss or damage suffered by such parties arising from their use of, reliance upon, or decisions or actions based on the Report or any of the Information ("improper use of the Report"), except to the extent those parties have obtained the prior written consent of AECOM to use and rely upon the Report and the Information. Any injury, loss or damages arising from improper use of the Report shall be borne by the party making such use.

This Statement of Qualifications and Limitations is attached to and forms part of the Report and any use of the Report is subject to the terms hereof.

AECOM: 2015-04-13

AECOM Canada Ltd.
410 – 250 York Street, Citi Plaza
London, ON N6A 6K2
Canada

T: 519 673 0510
F: 519 673 5975
www.aecom.com

Stephen Romano, P.Eng.
Environmental Service Engineer - Project Manager
The Corporation of the City of London
300 Dufferin Avenue
519-661-2489

October 26, 2020

Project #
60619503

Dear Mr. Romano;

Subject: Interim Asset Management Strategy: Arva Pumping Station to Huron Street Water Transmission Main Municipal Class Environmental Assessment Master Plan London, Ontario

AECOM is pleased to submit the final report entitled "Interim Asset Management Strategy".

In case you have any questions, please contact the undersigned for more details.

Sincerely,
AECOM Canada Ltd.

Khalid Kaddoura, PhD, P.Eng., PMP, ENV SP, CLSSBB
Project Manager/Asset Management Specialist, Water
khalid.kaddoura@aecom.com

John Hassan, PMP, CET
Senior Vice President
John.hassan@aecom.com

KK:cm
Encl.
cc:

Statement of Qualifications and Limitations

The attached Report (the “Report”) has been prepared by AECOM Canada Ltd. (“AECOM”) for the benefit of the Client (“Client”) in accordance with the agreement between AECOM and Client, including the scope of work detailed therein (the “Agreement”).

The information, data, recommendations and conclusions contained in the Report (collectively, the “Information”):

- is subject to the scope, schedule, and other constraints and limitations in the Agreement and the qualifications contained in the Report (the “Limitations”);
- represents AECOM’s professional judgement in light of the Limitations and industry standards for the preparation of similar reports;
- may be based on information provided to AECOM which has not been independently verified;
- has not been updated since the date of issuance of the Report and its accuracy is limited to the time period and circumstances in which it was collected, processed, made or issued;
- must be read as a whole and sections thereof should not be read out of such context;
- was prepared for the specific purposes described in the Report and the Agreement; and
- in the case of subsurface, environmental or geotechnical conditions, may be based on limited testing and on the assumption that such conditions are uniform and not variable either geographically or over time.

AECOM shall be entitled to rely upon the accuracy and completeness of information that was provided to it and has no obligation to update such information. AECOM accepts no responsibility for any events or circumstances that may have occurred since the date on which the Report was prepared and, in the case of subsurface, environmental or geotechnical conditions, is not responsible for any variability in such conditions, geographically or over time.

AECOM agrees that the Report represents its professional judgement as described above and that the Information has been prepared for the specific purpose and use described in the Report and the Agreement, but AECOM makes no other representations, or any guarantees or warranties whatsoever, whether express or implied, with respect to the Report, the Information or any part thereof.

Without in any way limiting the generality of the foregoing, any estimates or opinions regarding probable construction costs or construction schedule provided by AECOM represent AECOM’s professional judgement in light of its experience and the knowledge and information available to it at the time of preparation. Since AECOM has no control over market or economic conditions, prices for construction labour, equipment or materials or bidding procedures, AECOM, its directors, officers and employees are not able to, nor do they, make any representations, warranties or guarantees whatsoever, whether express or implied, with respect to such estimates or opinions, or their variance from actual construction costs or schedules, and accept no responsibility for any loss or damage arising therefrom or in any way related thereto. Persons relying on such estimates or opinions do so at their own risk.

Except (1) as agreed to in writing by AECOM and Client; (2) as required by-law; or (3) to the extent used by governmental reviewing agencies for the purpose of obtaining permits or approvals, the Report and the Information may be used and relied upon only by Client.

AECOM accepts no responsibility, and denies any liability whatsoever, to parties other than Client who may obtain access to the Report or the Information for any injury, loss or damage suffered by such parties arising from their use of, reliance upon, or decisions or actions based on the Report or any of the Information (“improper use of the Report”), except to the extent those parties have obtained the prior written consent of AECOM to use and rely upon the Report and the Information. Any injury, loss or damages arising from improper use of the Report shall be borne by the party making such use.

This Statement of Qualifications and Limitations is attached to and forms part of the Report and any use of the Report is subject to the terms hereof.

AECOM: 2015-04-13

Authors

Report Prepared By:

Khalid Kaddoura, PhD, P.Eng., PMP, ENV SP, CLSSBB
Asset Management Specialist

Report Reviewed By:

Chris Martire, M.Eng., P.Eng.
Senior Project Manager/Civil Engineer

Table of Contents

List of Figures

List of Tables

Appendices

1. Introduction

The City of London (City) retained AECOM to perform a Municipal Class Environmental Assessment Master Plan (EAMP) of a twinned 1050 mm PCCP from Arva Pumping Station to Fanshawe Park and a single 1050 mm between Fanshawe Park Road and Huron Street (Figure 1). As part of this assessment, the City is interested in conducting an interim asset management strategy of the same pipelines to preserve their performance during their service lives. The asset management scope includes a review of the available inspections and results and a short- and long-term asset management decision variables.

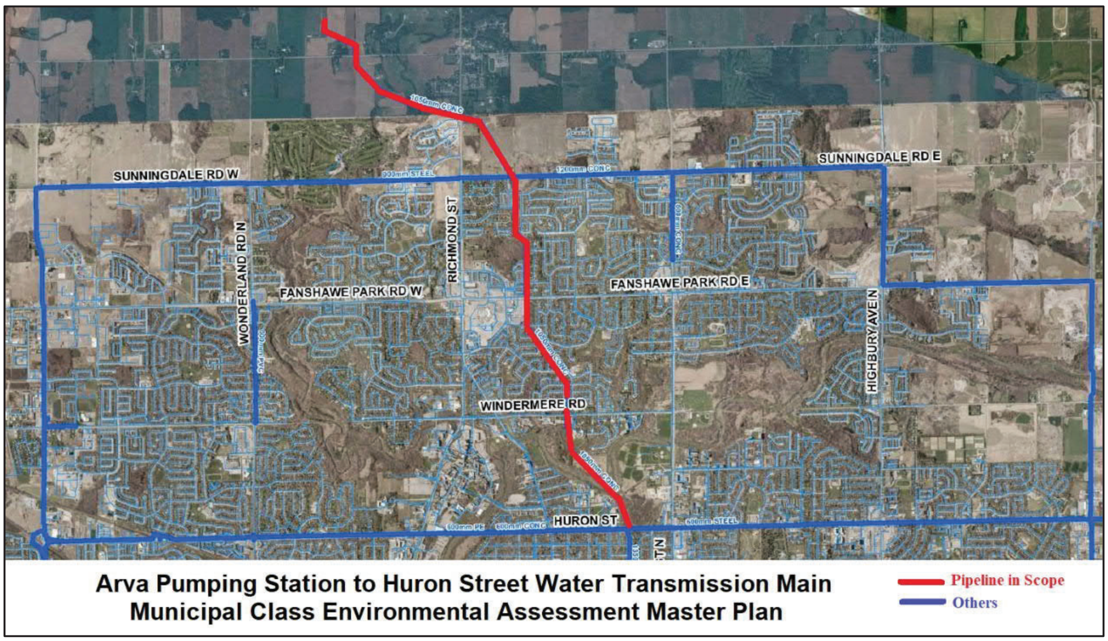


Figure 1: Arva Pumping Station to Huron EAMP PCCP Pipelines

1.1 Report Objectives

This report includes the requirements specified in AECOM's proposal (Task 3.2 – Development of an Interim Asset Management Strategy):

- Integrate condition assessment results and the recently developed risk framework to establish sustainable and optimum/near optimum short- and long-term alternatives.
- Rationalize decision variables based on an integrated criticality of the segments.
- Provide future screening, advanced condition assessment, and intervention requirements to potentially extend the service life of PCCP sections considering constructability and surrounding constraints.
- Establish a budgetary and conceptual cost estimate of potential strategies aimed at enhancing the condition of PCCP assets.
- Report the accuracy percentages used by referring to Association of Advancement of Cost Engineering (AACE) International Cost Estimate Classification.

2. Asset Management Review Summary

2.1 Summary of Inspections

The City of London utilized several inspection tools to assess the condition of the pipeline (**Appendix A**). As per Table 1, the records suggested that these inspections commenced in 2007 and the City installed Acoustic Fiber Optics (AFO), as a monitoring tool in 2010 to record potential wire breaks in a real-time manner.

Table 1: Pipeline Condition Assessment History

Inspection Year	Inspection Tool/Type	Distance (km)/Pipes ID
2007	SmartBall	~7 km
2007	Internal Visual and P-Wave Electromagnetic (EM)	~4 km
AFO System Installed in 2010-2012; Currently Monitoring	AFO	Arva Pumping Station to Chamber 12A (Pipe ID 0-0 to 11-226)
2014	Pipe Diver (PD)	~12 km
2015	PipeWalker	Pipe 1490 and 1492
2019 (Validation)*	Continuity Test Results	Pipes 1490 and 1492

*** Validation of pipe sections 1490 and 1492 occurred after their removal in December 2017**

Based on these inspections, the following was concluded:

Table 2: Condition Assessment Results

Type of Inspection	Comments
Leak Detection	• No leaks were detected along the inspected pipeline, considering that the lowest detection limit of the SmartBall was 0.5 US gal/min.
Wire Breaks	• Three anomalous segments were detected: ○ Segment 4-2 (station +26 from chamber 4) ○ Segment 8-173 (station 26+62 from chamber 8) ○ Segment 8-206 (station 31+90 from chamber 8) • Nine distressed pipes were observed between stations 222+95 and 227+34
Internal Visual	• Joints with missing mortar observed: ○ At stations 0+10, 0+15, 0+20; 67+80, 67+89, and 143+46 • Joints with corroding steel observed: ○ At stations 65+11, 67+85, 95+37,143+18,143+23, and 143+29

Besides those inspections, AFO sensors are installed along the majority of the pipeline [from Arva Pumping Station to Chamber 12A (station 233+09)]. Real-time wire break detection is not available for the portion beyond Chamber 12A to the end of the pipeline at Huron Street (station 249+00) (approximately 400 m).

According to the AFO and EM records, there are several segments with different detected wire breaks, but most of the wire breaks are recorded between stations 222+95 and 227+34. Along these stations, the internal visual inspection completed in 2007 was not performed and therefore, there is no direct information about the condition of the joints.

2.2 Summary of Risk Framework

Based on the inspections and available records, Pure Technologies Ltd. developed a Likelihood of Failure (LoF) model to aid in estimating the remaining useful life (RUL) of the pipeline. The LoF parameter was a component of the risk framework developed for large water main pipelines (**Appendix A**).

2.2.1 Likelihood of Failure

The LoF of pipes from Arva Pumping Station to Windermere Road ranged between Very Good (RUL is greater than 60 years) to Good (RUL is between 40 to 60 years) and the segment located to the south of Windermere Road to Huron Street was ranked as Adequate (RUL is between 20 and 40 years). The latter included the segments with the most frequent wire breaks along the watermain from Arva Pumping Station to Huron Street.

According to the LoF model, no immediate interventions are required as the minimum range of the RUL was estimated between 20 and 40 years.

Recently, the City contracted with Pure Technologies Ltd. to perform a Finite Element Analysis (FEA) to predict the performance of Class A-150 of 1050 mm embedded type with no-shorting strap PCCP (**refer to Appendix B**). The performance curve was developed considering a regular loading and the following limit states:

- Micro Cracking Limit
- Visible Cracking Limit
- Yield Limit
- The Strength Limit

While PCCP may structurally not fail at the Yield Limit but at the Strength Limit, it is mostly recommended to intervene prior to reaching this yield point (where either the wires or steel cylinder reaches their yield limits). At the Yield Limit, PCCP is expected to experience a number of wire breaks which would further decrease the overall structural capacity of the pipe. The impacts of the degradation would further increase in case the pipe is buried in a corrosive environment.

Based on the analysis and assumptions considered by Pure Technologies and with an internal pressure of 140 psi, the Yield Limit would be reached at 29 wire breaks. Therefore, a PCCP with more wire breaks at a non-varying internal pressure of 140 psi would be in the zone between the Yield Limit and Strength Limit. This zone increases the overall risk as the structural component is approaching the ultimate strength (either the wires or steel cylinder). Upon reaching the ultimate strength, the pipe is expected to fail. As per the analysis, the Strength Limit is reached at approximately 66 broken wires (considering a 140 psi internal pressure).

2.2.2 Consequence of Failure

As per the risk-management framework, the two most critical sections of the Arva Pumping Station to Huron Street pipeline are the segments located between Fanshawe Park Road East and Windermere Road and Windermere Road to Huron Street.

The pipeline crossing Fanshawe Park Road East through an easement runs between Masonville Square and 58 Fanshawe Park Road East. This pipeline runs through residential properties of the Masonville area, where it crosses Windermere Road between 531 Windermere Road and the Ivey Spencer Leadership Centre.

The other critical section runs East of 531 Windermere and heads south through the ravine area of North Branch Park, crosses underneath the Thames River. It also passes through the forested areas east of the London Campus of the International Centre for English Academic Preparation and Merrymount Family Support and Crisis Centre.

The other sections represented a group with minor consequences when compared to the aforementioned critical sections.

3. PCCP Examination and Assessment

PCCP material is a critical pipeline and mostly operates at a high pressure. Unlike many pipeline materials, PCCP's failure is known to be catastrophic and is likely to fail without warning. Therefore, it is necessary to consider assessment and examination options to monitor its condition during its service life.

Generally, understanding the condition of the asset follows sequential steps by commencing with a desktop-based model, field examination, and continuous monitoring. This generic sequence of activities would help in deciding on the future intervention actions that would further be based on a risk framework (e.g. prioritizing replacements/rehabilitation for high risk PCCP segments when compared to lower critical segments).

The City advanced in understanding the condition of the asset by implementing several condition assessment practices for more than a decade ranging from acoustic sensors to EM applications (Table 1). While AFO is considered a tool to monitor the condition of the pipe, these sensors would have limitations including, but not limited to the following:

- Wire breaks that occur while the monitoring system is shutdown for maintenance will not be recorded
- Although AFO are designed to record wire breaks in real-time, the failure mechanism of PCCP sections is complex and may fail due to a joint degradation
- In case a leak occurs prior to a PCCP failure, AFO system will not be able to capture it

In general, soil sampling, testing, and analysis is one of the many ways to prepare a responsive asset management strategy. The following section includes a description of the purpose of conducting soil sampling that is applicable to buried pipelines and mainly concrete pressure pipes. The results of the recent soil sampling and analysis are described in Section 4.2.1.

3.1 Soil Sampling

Soil type can have a significant influence on the external condition of the pipe. Granular soils such as sand and gravel are typically less corrosive than clay soils due to their ability to conduct electrical currents attributable to the saturation levels of the soil. The corrosivity of the buried soil is a direct correlation to external corrosion commonly resulting in pitting of the exterior surface for metallic pipes and degradation of the mortar coating of PCCP, exposing the prestressing wires to the corrosive environment.

The chloride content of the surrounding soils adjacent to a pipeline is an important indicator of pipeline condition. The concentration of chlorides (Cl_2) within the soil can have corrosive effects on PCCP pipes as they can attack the pipe by penetrating through porous concrete and corrode the steel prestressing wires and cylinder. The presence of chlorides in the soil results in a lower soil resistivity, which promotes the corrosion process. Soil resistivity is a strong measure of the potential for the soil to support corrosive activity and as such is a good indicator of likely pipe condition. Chlorides can either be naturally occurring or artificially introduced in soils through de-icing process.

The concentrations of sulphate ions (SO_4) in soil can react with hydration products present in hardened cement, including calcium hydroxide, silicate hydrate to form two different by-products: 1) Ettringite, which causes the volume of the concrete matrix to increase leading to cracking or 2) Gypsum ($CaSO_4$ x $2H_2O$), which can soften concrete. Either of these two chemical reactions weakens the concrete structure with prolonged exposure. The evaluation of sulphides (S_2) in the soil is a value added; however, the sulphide content has negligible impact on concrete pipe.

The pH is a measure of the acidity or alkalinity of the soil material. Typically, alkaline soils (pH>7.5) on their own do not pose any corrosive risk. However, under certain conditions in the right environment, the pH of a soil can display corrosive tendencies and display corrosive effects on PCCP watermains.

Electrical conductivity is the measure of a materials ability to conduct an electric current whereas the soil resistivity is its inverse. The resistivity is a measure of how much the soil resists electricity. The soil resistivity values are used to rank the corrosivity of the soil. The higher the resistivity the progressively less corrosive a soil will be. Soil resistivity is a major indirect indicator of the degree of corrosivity of an environment. and when coupled with visual classification methods, spikes in decreased resistivity are often associated with localized increases in chloride content. The presence of chlorides is extremely valuable in highlighting spot locations that increase the potential for increased deterioration of concrete pressure pipes.

3.2 Examination of Pipes In-situ

3.2.1 Locating Test Pits

Upon collecting soil samples and determining the extent of soil corrosivity, the locations for test pit assessment will be identified. While soil corrosivity is one of the essential factors in selecting test pit locations, some other factors would further assist the City as follows:

- **Pipe depth** – deeper pipelines will increase costs of excavation
- **Soil type and presence of groundwater** – weak soil accompanied by groundwater table would require specific shoring system to offer a safe area for the inspector to directly access the test pit and assess the pipeline segment.
- **Vulnerable locations** – joints are one of the most problematic areas for water pipelines where improper field applied mortar is common. In many instances, PCCP pipelines resulted in significant consequences due to joint failures. Further, one of the major limitations of EM tools is their reduced capabilities in detecting wire breaks at

a close proximity to joints. Where soil is corrosive and previous internal assessment (Table 2) identified degraded areas, these locations may be prioritized for further assessment.

- **Lack of condition information** – due to logistics and enabling work requirements to utilize inspection technologies, some segments may not be inspected/monitored. Although AFO sensors are installed along the majority of the pipeline length, segments between station ~233+09 (chamber 12A) to station ~249+00 do not have these monitoring systems.
- **Baseline location** – baseline location would be necessary to perform assessment where no degradation or corrosion is anticipated and then compare the results with locations with high risk of degradation. This comparison offers an opportunity to understand the mechanism of degradation.

3.2.2 Destructive and Non-Destructive Examinations

Pipes may be externally examined in-situ, at isolated locations or internally via confined spaces entry for larger diameter pipes. Examination can be accomplished using traditional tools such as visual inspection and sounding with masonry hammers however, the deterioration that can occur in PCCP may be difficult to assess through visual classification methods alone. Therefore, specialized tools and inspection methods have been developed to facilitate a more refined, more convenient, and more thorough method of pipeline condition assessment.

These specialized tools fall into two distinct categories of evaluative examination: destructive and non-destructive. Destructive methods typically involve techniques which alter the pipe specimen in such a way that it is no longer deemed suitable for replacement into service. Non-destructive examination (NDE) methods can be defined as those that yield information about the pipe without affecting its serviceability.

Destructive examination, which can be undertaken through either reactive / opportunistic or planned investigations, involves the physical examination of pipe sections that have been removed from the watermain, and generally takes place in a laboratory. This type of testing usually is performed on specimens collected from the watermain when repairs and upgrades are undertaken. Sampling of pipe and soil materials can provide insight to valuable information including:

- Remaining pipe strength;
- Integrity of coatings or wrap;
- Type and extent of corrosion of the wires, and
- Soil corrosivity, by way of chemical/electrochemical analysis of the soil surrounding the pipe (e.g. resistivity, soluble ion concentrations, pH, etc.).

NDE generally refers to specialized inspection methods that provide condition information about materials without destroying them or impairing their future usefulness. NDE techniques have been developed to permit both rapid and qualitative inspection and condition assessment of various materials from their surface and beyond, at both isolated locations and continuously along the watermain's length. Techniques developed for assessing PCCP are the most refined and proactive in nature, providing the opportunity to prevent failures and plan repairs.

A comparison between the two methods shows that each can yield subtly different information, but in each case, valuable information can be inferred about the pipe condition, rate of deterioration, and expected design life. Table 3 provides a basic list of a few properties that can be gathered through each examination method.

Table 3: Properties Determined from Destructive and Non-Destructive Testing

Destructive Examination	Non-Destructive Examination (NDE)
• Strength • Hardness • Metallography • Corrosion characteristics and cause • Coating condition	• Leaks • Cracking • Soil / groundwater chemical composition and electrical properties

3.2.3 Testing of PCCP Pipe Specimens

PCCP is a composite steel and concrete pipe product that is manufactured by helically winding prestressing wires, under tension, around a pipe core, then coating the wire with a layer of cementitious mortar to protect it from corroding. The effect of the mortar coating serves as a barrier to isolate the steel from the environment and while providing an alkaline environment that passivates the steel and prevents corrosion from occurring. Bituminous coatings, corrosion inhibitors and other construction chemicals may be applied to the exterior of the finished pipe to isolate the mortar from the environment and impede absorption of groundwater or chemicals.

If opportunities arise that enable some or all these pipe components to be salvaged for laboratory examination and testing, consideration should be given to determining the following physical and chemical parameters, all of which provide insight into the structural capacity and extent of degradation of the pipe:

- Basic dimensional properties including cylinder thickness, prestress wire diameter and spacing, inner and outer concrete core thickness, and mortar coating thickness (Figure 2).
- Tensile strength testing of the steel pipe cylinder in accordance with ASTM A370[1] - Annex 2. Multiple test specimens should be taken at different orientations in the cylinder because tensile strength may vary with direction due to the rolling process used to manufacture the steel (Figure 3).
- Tensile testing of the prestressing wire in accordance with ASTM A370 – Annex 4.
- Torsional ductility testing of the prestressing wire in accordance with ASTM A938[2].
- Compressive strength testing of the concrete core in accordance with ASTM C109[3], which defines a procedure for testing compressive strength using cubic specimens.
- Cement degradation testing by application of pH indicator (Figure 4).
- Petrographic analysis of the mortar coating and core concrete to evaluate quality of manufacture, presence of protective chemicals or treatments, and extents of chemical and mechanical deterioration.
- Evaluation of mortar or concrete degradation using Semi-Quantitative X-Ray Diffraction (XRD) analysis to identify the mineralogical composition of the samples.

---

[1] ASTM International, Standard A370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products.
[2] ASTM International, Standard A938, Standard Test Method for Torsion Testing of Wire.
[3] ASTM International, Standard C109/C109M, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-inch or 50mm Cube Specimens).

Figure 2: Underside of Mortar Coating from PCCP, Revealing Wire Diameter and Spacing.

Figure 3: Tensile Specimen Locations in Steel Cylinder (note weld along top of coupon)

Figure 4: Cement Degradation (pH) Test of Concrete Pipe Core.

3.3 PCCP Pre-Stressing Wire Assessment

The main principal of the EM technology in PCCP applications is based on a magnetic field generated by the coil through the liner and into the pipe wall. Pure Technologies Ltd. has deployed this technology for PCCP pipe inspection using man entry and crawler configurations for out-of-service inspections and launched off their PD platform for live in-service inspections (Figure 5). The specifications of these are listed in Table 4.

Analysis of EM data can be problematic if the manufacturing details of the pipes are not known, or if there are any EM influences along the pipeline. Some key issues and limitations of the EM technology to be aware of include:

- Tool calibration – as with any measuring tool or technology, the accuracy of the measurements made using the tool is only as good as the accuracy and care with which the tool has been calibrated. The best inspection results will be achieved when the tool has been calibrated using each type and class of pipe in the pipeline being inspected. However, since the calibration process is destructive, it is usually not possible to calibrate the tool using pipes in the inspected pipeline, and owners rarely if ever have spare pipes in storage that can be used for that purpose. Consequently, service providers usually rely on their “library” of historic calibration curves (derived from previous tests) to calibrate the tool for inspections. However, because manufacturers can construct the required class of pipe using any combination of cylinder thickness and wire gauge (and wire spacing) available in their material inventory at any given time, historical curves may not be truly representative of the actual pipes installed in the line.

- Influence of Joint Rings – Although EM technology can detect a single wire break in the middle portion of a pipe, wire breaks within 0.3 m to 0.6 m from the ends of the pipes cannot be detected due to the magnetic field created by the comparatively large mass of steel in the joint rings.

- Grouting Condition – Pipe segments with poorly grouted or deteriorated joints, would be at higher risk of failure, particularly in aggressive environments. If the joint rings begin to corrode and eventually cause the pipe’s mortar coating to spall and expose the underlying wires, localized deterioration is expected. Such conditions are not detectable using EM technology. Potential scenarios may occur at joints were some deterioration observations were recorded (refer to Table 2).

- EM Influence – Since EM technology detects variations in the magnetic field, any external EM sources such as high-tension power lines, or ferromagnetic materials such as pipe casings and iron-bearing backfill materials, may influence the magnetic fields detected by the tool.

- Detection of Pipe Distress – Since EM technology can only detect variations in the magnetic fields induced in the steel components of the pipes being inspected, it cannot detect distress in the concrete components. Therefore, it could not detect the deterioration of the pipe's external mortar coating until such time as the pre-stressing wires began to break.

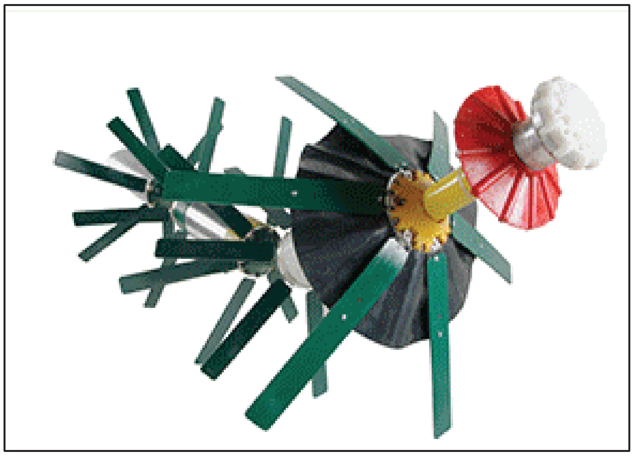


Figure 5: PipeDiver Launching Platform

Table 4: PureEM Platforms

Parameter	Manned EM	PipeDiver (PD)	Robotics
Tool Size Available / Pipe Sizes Inspected	900 mm to 1200 mm	400 mm to 1200 mm	600 mm to >1500 mm
System status during insertion/extraction	Out of Service	Temporally out of service or operated via by-pass	Out of Service (Depressurized)
System status during inspection	Out of Service	In Service	Depressurized
Insertion requirements	Access flange (min. 500 mm)	Access flange (min. 300 mm)	Access flange (min. 450 mm) or 350 mm x 400 mm access
Extraction	Access flange (min. 500 mm)	Drop chamber, stopping device and new access flange (min. 300 mm)	Same as insertion (using winching)
Operation demands	Dewatering	Pressure max 250 psi and 0.15 -0.6 m/s (0.5f/s-2.0 f/s) (metallic pipelines)	Depressurized
Major limitation	Air ventilation, Debrides, slopes, passing obstacles along the pipeline	Flow rates, inline features, pipe configuration (Bends), Battery life 20 Hours	Debrides, data quality, slopes, pipe configuration layout, number of cumulative bends
Cylinder Thickness	12 mm and less	12 mm and less	12 mm (½") and less
Lining	Up to 12 mm of non-metallic lining	Up to 12 mm of non-metallic lining	Up to 12 mm (½") of non-metallic lining
Calibration required	YES	YES	YES

4. Asset Management Strategy

In any asset management strategy, there are several options that can be considered during the service life of an asset. These actions can be in the form of:

- Do nothing;
- Short-term; and
- Long-term

This strategy considers a budgetary cost estimate for the different considered asset management options. The budgetary estimate is prepared by considering a Class 4 Estimate Class in Accordance to the Association for Advancement of Cost Engineering (AACE), shown in Table 5.

Table 5: AACE International Recommended Practice No. 18R-97 for Cost Estimate Classification

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

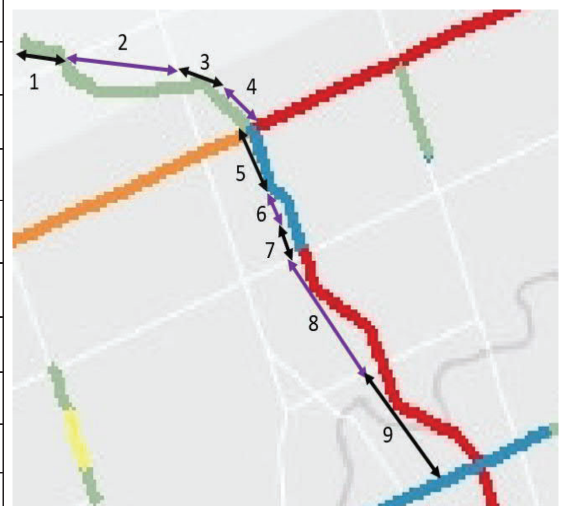
The initial budgetary costs considered are based on 2020 value. In order to account for both the nominal interest rate and the inflation rate, the Fisher formula (Equation 1) is used. The inflation rate is considered as 2% and the nominal interest rate is assumed to be 3%. The calculated real interest rate (1%) will be applied to find the net present value so that it can be compared with the “do nothing” option.

4.1 Do Nothing

The “do nothing” option would indicate that the City accepts the risk of the pipeline to fail without conducting preventative maintenance or monitoring actions. In real world, this option is minimally implemented especially when it comes to critical assets such as transmission mains.

The “do nothing” option is approximately quantified at $164 M (from Pure Technologies Ltd. risk framework discussed in **Appendix A**). The aggregated costs were based on the maximum of each range for each parameter, excluding the Economic parameter as it is related to replacement costs. Since the analysis assumes a “do nothing” option, replacement is deducted from the total monetized CoF value. Therefore, the $164 M would refer to the cost of failure due to social and environmental factors based on the assumptions stated in Table 6.

Table 6: Do Nothing Monetized CoF

Segment*	Social Level of Service	Social - Property Damage	Social Road Traffic	Social Railway	Environmental Aquatic Life	Total	Segmentation*
1	$5.0 M	$1.0 M	$.1 M	$0.0 M	$.001 M	**$6 M**	
2	$5.0 M	$1.0 M	$.1 M	$0.0 M	$.030 M	**$6 M**	
3	$5.0 M	$1.0 M	$.1 M	$0.0 M	$.001 M	**$6 M**	
4	$5.0 M	$1.0 M	$.5 M	$0.0 M	$.001 M	**$7 M**	
5	$2.0 M	$2.0 M	$.5 M	$0.0 M	$.001 M	**$5 M**	
6	$2.0 M	$2.0 M	$.1 M	$0.0 M	$.001 M	**$4 M**	
7	$2.0 M	$5.0 M	$.5 M	$0.0 M	$.001 M	**$8 M**	
8	$55.0 M	$5.0 M	$2.0 M	$0.0 M	$.001 M	**$62 M**	
9	$55.0 M	$5.0 M	$1.0 M	$0.0 M	$.001 M	**$61 M**	
Total**	**$136.0 M**	**$23.0 M**	**$4.9 M**	**$0.0 M**	**$.0380 M**	**$164 M**	

*** Segmentation may differ from** the actual analysis **depending on Pure** Technologies Ltd. **assessment and segmentation procedure.** Segmentations were determined based on the color codes of all parameters’ evaluated from Arva Pumping Station to Huron Street. Accordingly, nine different segments were used to estimate the CoF.
**** Each monetized CoF rating was based on the upper limit of each parameter. Where** the **upper limit was not available, an assumed value was considered by taking into consideration the preceding ranges' differences.** Therefore, the total value may be over or underestimating the actual computations. **The Economic parameter was excluded as it referred to "Replacement". Since the** r**eplacement vs.** d**o nothing is analyzed, the Economic monetized value was excluded from the Co**F.

4.2 Short-term Actions

A determinate period for short-term actions would vary from one decision-maker to the other but in this assignment, these actions are mostly related to monitoring or examining the state of the PCCP at a certain frequency. As some joints were observed to have some deficiencies (Table 2), and in case repairs were not performed, these joints would potentially have degraded. Corroded steel observations at joints should be prioritized for repairs during the short-term period followed by repairs to joints with mortar loss observations. As mortar loss observations were observed for more than a decade and considering no repairs were performed, excessive mortar loss is relatively going to be expected and may have exposed steel to the surrounding environment. Therefore, interior joint repairs would be considered in this strategy.

The regular inspection and maintenance of watermain chambers, valves and associated appurtenances are essential components of watermain management. The strategic closure of one or more watermain valves in the event of a watermain failure is necessary to ensure an efficient response to stop the flow of water where valve condition and operation become critical. Regular clearing of access routes and the interior clearing of accumulated debris associated with each chamber can improve response times during a failure. Routine inspection and maintenance of watermain chambers are proactive measures to ensure peak performance and the level of service of the watermain and its associated components.

The actions and their associated costs are provided in Table 7 and Table 8, respectively.

Table 7: Monitoring and Examination Options

Action	Frequency	Comment
Inspection and Maintenance of Valves and Chambers	Annual	From a Levels of Service (LoS) measure, inspection and maintenance of valves and valve chambers is required to avoid impacts to the loss of physical integrity of the chamber and valves. This include replacing damaged valves, chamber cleaning where required, missing air vents, minor rehabilitation of chambers, etc. 100% of the valves and chambers should be inspected/maintained annually.
Soil Sampling and Testing	Every 15 Years	Reduced resistivity of soil is one of the contributing factors to increased deterioration of PCCP. Due to de-icing, chloride levels may elevate and would further decrease the resistivity levels. Therefore, understanding the soil characteristics at a frequent basis would provide additional insights for interventions.
Test Pits	Every 15 Years	Test pits would offer direct information about the condition of the pipe, depending on the type of examination. Joints at corrosive soil should be monitored at a certain frequency to understand the level of intervention.
Free-Swimming EM	Every 15 Years	Although AFO is installed along the pipeline, the EM tool would still be considered as an option to confirm the extent of the wire break. After any EM inspection, a baseline of the state of the pipeline is updated.
Repair of Joints	Based on Assessment	Joints are mostly assessed based on internal or external examination. The deterioration of joints is hardly captured by EM technologies. The impact of soil envelope may increase the degradation level of joints.

Table 8: Monitoring and Examination Options Budgetary Cost Estimates

Item	Budgetary Unit Cost Estimate in 2020	Unit	Comments
Inspection and Maintenance of Valves and Chambers	$2,500	Each	Includes half day of inspections (high-level) and a budget for low to moderate interventions. The total number of chambers = 26 The same unit rate applies to all annually. This could balance cost variations; in case some assets need more than the budgeted amount and others do not need interventions.
Soil Sampling and Testing	$1,200	Each	Including auguring and soil testing.
Test Pits (3 m x 3 m x depth varies)	$25,000	Each	Includes excavation, backfilling, and inspection. However, this cost is dependent on the complexity of the site and type of in-situ assessment. This strategy is implemented frequently to monitor the progression of the deterioration.
Free-Swimming EM	$100,000	Inspection	Price may differ depending on enabling work requirements. For example, a 7,000 m inspection would cost $520,000 ($100,000 + 60/m * 7,000 m) Length of pipes including twinned sections = 12.3 km
	$60	m	
Joint Repair (Interior Grouting)	$5,000	Each	Repairs would require draining and access to interior. Removal of corroding material and grouting.

Collecting as much information about the Arva Pumping Station to Huron Street pipeline relative to the existing conditions associated with the pipe can be accomplished while conducting geotechnical investigations or external evaluations of the Arva to Huron pipeline. The collection of soil samples in direct contact with the pipe and evaluating its corrosivity and other associated properties can provide further insights into the interaction of the soil with the pipe's concrete matrix. Conducting visual inspections of the exterior of the pipe, at any opportunity, for features such as, blistering, pitting, voids in mortar diaper (if joints are exposed) are all indications of the pipe degradation.

Soil parameters vary along the length of the pipeline and are also a characteristic of the bedding and backfill used at installation. Similarly, operational characteristics may impact the overall hydraulics along the pipelines. Results from the geotechnical and hydraulic analysis performed during Summer 2020 are discussed in the next section.

4.2.1 Geotechnical Analysis

4.2.1.1 Overview

Soil testing was performed on 19 soil samples (**Appendix C**). These soil samples were located on different sections along Arva Pumping Station to Huron Street. The boreholes' locations are identified based on their segment locations (from-to) as per Table 9. The table also displays the LoF assigned and as reviewed in **Appendix A**.

Table 9: Borehole From-To Locations

Sample	From	To	LoF
BH-1 TW-3	Richmond Street	Richmond Street	Adequate
BH-2 TW-3	Richmond Street	Richmond Street	Very Good
BH-2 TW-4	Richmond Street	Richmond Street	Very Good
BH-4 TW-3	Sunningdale Road	Fanshawe Parkway	Very Good
BH-6 TW-3	Sunningdale Road	Fanshawe Parkway	Very Good
BH-7 TW-3	Fanshawe Parkway	Windermere Road	Adequate
BH-8 TW-3	Fanshawe Parkway	Windermere Road	Adequate
BH-14 TW-2	Windermere Road	Huron Street	Fair
BH-15 TW-2	Windermere Road	Huron Street	Fair
BH-16 TW-2	Windermere Road	Huron Street	Fair
BH-17 TW-3	Windermere Road	Huron Street	Fair
BH-18 TW-2	Windermere Road	Huron Street	Fair
BH-18 TW-3	Windermere Road	Huron Street	Fair
BH-19 TW-3	Windermere Road	Huron Street	Fair
BH-20 TW-3	Windermere Road	Huron Street	Fair
BH-21 TW-3	Windermere Road	Huron Street	Fair
BH-22 TW-3	Windermere Road	Huron Street	Fair
BH-23 TW-3	Windermere Road	Huron Street	Fair
BH-24 TW-3	Windermere Road	Huron Street	Fair

The collected samples were tested to determine the corrosivity level of soil using the American National Standards Institute/American Water Works Association (ANSI/AWWA). The soil corrosivity test results include a measurement of the following concentrations and parameters:

- Chloride
- Sulphate
- Sulphide
- Resistivity
- pH
- Redox
- Moisture

ANSI/AWWA Corrosivity Score

According to ANSI/AWWA, a score of 10 points or greater indicates that the soil is corrosive to buried infrastructure; specifically, assets containing metallic/ferrous components such as PCCP (steel cylinder and prestressing wires). As per the geotechnical report (**Appendix C**), the majority of the scores are below 10, while some others are closer to the corrosivity threshold (refer to Table 10). ANSI/AWWA scores of 18.5 were observed in a location close to Richmond Street (BH-2 TW-3 and TW-4).

Table 10: ANSI/AWWA Corrosivity Scores

Sample	ANSI/AWWA Soil Score	ANSI/AWWA Corrosive if 10 or Greater
BH-1 TW-3	5	Below 10
BH-2 TW-3	18.5	Corrosive
BH-2 TW-4	18.5	Corrosive
BH-4 TW-3	3	Below 10
BH-6 TW-3	3	Below 10
BH-7 TW-3	6.5	Below 10
BH-8 TW-3	8.5	Below 10
BH-14 TW-2	6.5	Below 10
BH-15 TW-2	6.5	Below 10
BH-16 TW-2	3	Below 10
BH-17 TW-3	6.5	Below 10
BH-18 TW-2	8	Below 10
BH-18 TW-3	5	Below 10
BH-19 TW-3	9.5	Below 10
BH-20 TW-3	6.5	Below 10
BH-21 TW-3	6	Below 10
BH-22 TW-3	4	Below 10
BH-23 TW-3	3	Below 10
BH-24 TW-3	8.5	Below 10

Further analysis of soil testing components was conducted to determine the relative corrosivity of the parameters on existing buried assets.

Chloride

The concentration of chlorides present in the soil can increase the corrosivity of the soil. Their contribution to the corrosion process is significant, and at high concentrations, they may cause severe corrosion contributions. Chlorides promote corrosion due to their conductive nature.

Chloride ions can originate from brackish groundwater, and de-icing of roads and can vary based on the season. The resistivity of soil increases with the decrease in chlorides, sulphide, and sulphate. Table 11 shows the relation between the relative corrosivity and concentration of the chloride.

Table 11: Chloride Concentration and Relative Corrosivity (Peabody 2001) [4]

Chloride Concentration (ppm)	Relative Corrosivity
>5000	Severe
1500-5000	Considerable
500-1500	Moderate
<500	Low

Based on the geotechnical results, all soil samples collected within a proximity to Huron Street have lower chloride concentrations (<500 ppm). According to Table 11, this suggests that the relative corrosivity of those segments, considering chloride concentrations, would be lower. However, soil samples collected closer to Richmond Street have higher chloride concentrations. Based on the borehole locations, these samples were collected at a closer proximity to Richmond Street, where de-icing activity may have contributed to increased salts in the soil and elevated the chloride content.

Sulphate and Sulphide

Sulphate attack is the most common form of chemical attack that the concrete would be exposed to. This type of attack originates from surrounding soil, penetrate into concrete and react with the cement paste. Soil with sufficient concentration of sulphates may result in the deterioration of concrete including the propagation of cracks and the reduction of the strength of the affected concrete. Degraded concrete components could result in the exposure of the prestressing wires and steel cylinder to the outer environment (ground) which increase the vulnerability of the asset.

Therefore, a sound concrete component in PCCP is essential to minimize the impacts of any electrochemical process between the wires, cylinder and the soil. Table 12 shows the sulphate concentration and relative corrosivity as per the Canadian Standard Association (CSA).

Table 12: Sulphate Concentration and Relative Corrosivity

Sulphate Concentration (ppm)	Relative Corrosivity
>10,000	Very Severe
1500-10,000	Severe
150-1500	Moderate
1-150	Low

[4] Peabody, A.W. (2001) *Peabody's Control of Pipeline Corrosion*, NACE International, Houston, TX.

Most of the sulphate readings and the corresponding qualitative ratings, in accordance to the CSA, suggest that the relative corrosivity exposure due to sulphate is Moderate. The majority of the soil samples collected along the segments between Windermere Road and Huron Street have sulphate concentration values between 150 and 10,000 ppm (localized as per the borehole samples). This indicates, according to the CSA, that the segments along these roads are exposed to Moderate to Severe relative corrosivity.

Resistivity

Soils that exhibit low resistivity are considered corrosive since they promote electrochemical reactions to occur more readily. Soil resistivity will vary with variations in both moisture content and ionic soluble salt concentration. Although there is some variation in the literature as to the degree of corrosiveness that is associated with certain resistivity values, typical values and their associated significance are shown in Table 13.

Table 13: Corrosion Activity of Ferrous Metals based on Soil Resistivity

NACE[5]	
Resistivity Range, ohm-cm	*Corrosion Activity*
0 – 500	Very corrosive
500 – 1000	Corrosive
1000 – 2000	Moderately corrosive
2000 – 10,000	Mildly corrosive
>10,000	Negligible

The majority of the soil samples are Mildly Corrosive based on the results of the geotechnical investigation and considering NACE qualitative corrosion activity. However, soil samples collected within proximity to Richmond Street have higher conductivity values and are Very Corrosive. The literature shows that the chloride content and conductivity levels have almost a direct positive relationship between each other (an increased level of chloride will increase the conductivity of soil and vice versa). At those specific locations, the chloride results were higher than the other soil samples; indicating a higher corrosion process to prestressing wires.

Soil Hydrogen Ion Activity (pH)

A measure of the soil's hydrogen ion activity (pH) can also provide an indication of the soil's corrosiveness. Iron corrosion testing by Uhlig[6] suggests that a protective layer of corrosion product forms at the iron's surface in the soil pH range of 4 to 9.5.The rate of corrosion within this pH range is dependant mainly upon the availability of oxygen to participate in the corrosion process (the rate at which oxygen moves through the layer to the iron's surface). At pH levels below 4, this protective layer is dissolved, and the corrosion process proceeds more readily. At pH levels above 9.5 this protective layer may be impervious, and the corrosion rate decreases. Since pH and soil corrosiveness vary with soil temperature and soil composition, the relationship is presented in Table 14.

[5] *A.W. Peabody, "Control of Pipeline Corrosion – Second Edition", p.88, (2001).*
[6] *Herbert H. Uhlig, The Corrosion Handbook, John Wiley & Sons, Inc., p.129-130, (1948).*

Table 14: Anticipated Impact of pH on Corrosion of Buried Ferrous Metals[7]

pH	Degree of Corrosivity
<5.5	Severe
5.5-6.5	Moderate
6.5-7.5	Neutral
>7.5	None (alkaline)

Based on the geotechnical investigation, all soil samples collected along the pipeline are alkaline and have reduced to noncorrosive impacts on the prestressing wires.

Redox Potential

The value of soil redox potential is dependent on the dissolved oxygen content in the pore water and can further provide indications about the conditions in which reducing bacteria in soil could grow sulphate. Generally, low values of redox potential would suggest that the conditions are appropriate for anaerobic microbiological activity. The Redox Potential values found in most of the soil samples were higher than 100 mV. According to AWWA, this value does have a significant impact on the corrosion mechanism.

Moisture Content

The presence of water in a soil acts as an electrolyte for the electrochemical corrosion reactions. Higher contents of water indicate a higher probability of a corrosion mechanism. Moisture content along with other factors such as the water retention capacity, groundwater level and water mobility in soil are some of the factors that can be taken into account while studying the corrosion of soil. AWWA describes the corrosivity contribution of the moisture based on three attributes:

1. Poor drainage, continuously wet
2. Fair drainage, generally moist
3. Good drainage, generally wet

The moisture content of the tested samples ranged between 9 and 22%. At this range of moisture content and given the groundwater table was not monitored along all collected samples, it will conservatively be considered as “generally moist”.

4.2.1.2 Summary

The summary of the parameter analysis findings is shown in Table 15. There is a wide variation in soil contributing to degradation based on the soil investigation. Generally, the soil does not seem to be aggressively corrosive along all the sections; however, some localized degradation of the concrete and prestressing wires is expected.

The results have shown higher concentrations of sulphates between Windermere Road and Huron Street. This may indicate that the concrete along those specific locations is subjected to concrete degradation. While the pH and chloride ions have relatively reduced degree of corrosion, the conductivity and redox potential of soil are most likely going to be corroding factors. In case prestressing wires have been exposed to the soil environment and/or corrosive products penetrated through concrete pores, prestressing wires could be corroded. Therefore, corrosion products could be observed on the concrete surface. By reviewing the wire breaks recorded along Arva Pumping

[7] *A.W. Peabody, Control of Pipeline Corrosion – Second Edition, p. 91, (2001).*

Station and Huron Street, the majority of the wire breaks are occurring along Windermere Road and Huron Street. By relating the geotechnical investigation results with the wire break distribution and locations, the environment surrounding the asset has an impact on degrading the asset. The analysis of the conducted soils investigation along this pipeline, specifically between Windermere Road and Huron Street, supports that corrosive soils directly contributed to the degradation PCCP within this region and subsequent removal the two PCCP pipe sticks removed in December 2017.

Table 15: Soil Sample Parameters Analysis

Borehole	From	To	LoF	Chloride	Sulphate	pH	Conductivity/ Resistivity	Redox Potential	Moisture Content
BH-1 TW-3	Richmond Street	Richmond Street	Adequate	Moderate	Low	None	Mildly Corrosive	Significant	Generally Moist
BH-2 TW-3	Richmond Street	Richmond Street	Very Good	Severe	Moderate	None	Very Corrosive	Below Threshold	Generally Moist
BH-2 TW-4	Richmond Street	Richmond Street	Very Good	Severe	Moderate	None	Very Corrosive	Below Threshold	Generally Moist
BH-4 TW-3	Sunningdale Road	Fanshawe Parkway	Very Good	Low	Low	None	Mildly Corrosive	Significant	Generally Moist
BH-6 TW-3	Sunningdale Road	Fanshawe Parkway	Very Good	Low	Moderate	None	Mildly Corrosive	Significant	Generally Moist
BH-7 TW-3	Fanshawe Parkway	Windermere Road	Adequate	Low	Moderate	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-8 TW-3	Fanshawe Parkway	Windermere Road	Adequate	Low	Moderate	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-14 TW-2	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-15 TW-2	Windermere Road	Huron Street	Fair	Low	Low	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-16 TW-2	Windermere Road	Huron Street	Fair	Low	Low	None	Mildly Corrosive	Significant	Generally Moist
BH-17 TW-3	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-18 TW-2	Windermere Road	Huron Street	Fair	Low	Severe	None	Moderately Corrosive	Significant	Generally Moist
BH-18 TW-3	Windermere Road	Huron Street	Fair	Low	Severe	None	Mildly Corrosive	Significant	Generally Moist
BH-19 TW-3	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Below Threshold	Generally Moist
BH-20 TW-3	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Significant	Generally Moist
BH-21 TW-3	Windermere Road	Huron Street	Fair	Low	Low	None	Mildly Corrosive	Significant	Generally Moist
BH-22 TW-3	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Significant	Generally Moist
BH-23 TW-3	Windermere Road	Huron Street	Fair	Low	Moderate	None	Mildly Corrosive	Significant	Generally Moist
BH-24 TW-3	Windermere Road	Huron Street	Fair	Low	Low	None	Mildly Corrosive	Below Threshold	Generally Moist

4.2.2 Hydraulic Modelling Analysis

Transients occur when the system changes from one steady state condition to another due to a control action at a hydraulic device. This change result in a variation of the flow velocity causing a rapid or gradual change in pressure (increase or decrease). A transient modelling was performed by AECOM on the existing pipeline from Arva

Pumping Station to Springbank Reservoir (approximately 18 km). The transient modelling simulated the power failure at Arva Pumping Station during high pumping scenarios (considered to be the worst case). The analysis showed the impact of this simulation for the minimum and maximum surge pressures along the pipe (Figure 6). For more details, refer to **Appendix D**.

The pipe considered in this assignment is represented by the green arrow starting from 0 m at Arva Pumping Station to Chamber 13 at approximately 7.5 km to the pumping station. Based on the elevation of the pipe and the maximum Transient HGL head, the overall maximum HGL is the greatest between Windermere Road and Huron Street. The maximum working and surge pressure (internal pressure) is observed at approximately 6 km from Arva Pumping Station. At this point, the difference between the elevation of the pipe and the Maximum Transient HGL is the highest. The elevation of the pipe at this location is approximately 230 m and the HGL head is 314 m. Based on these elevations, the pressure head would be 84 m, which corresponds to 119 psi. This location is closest to Windermere Road in the section running between Windermere Road to Huron Street. Overall, the minimum HGL that is simulated does not vary much along the same pipe. The minimum HGL along the same segment ranges between (46 m [65 psi], and 50 m [70 psi]).

From the historical data received, the observed breaks are mostly recorded along the same section where the highest maximum transient HGL is recorded.

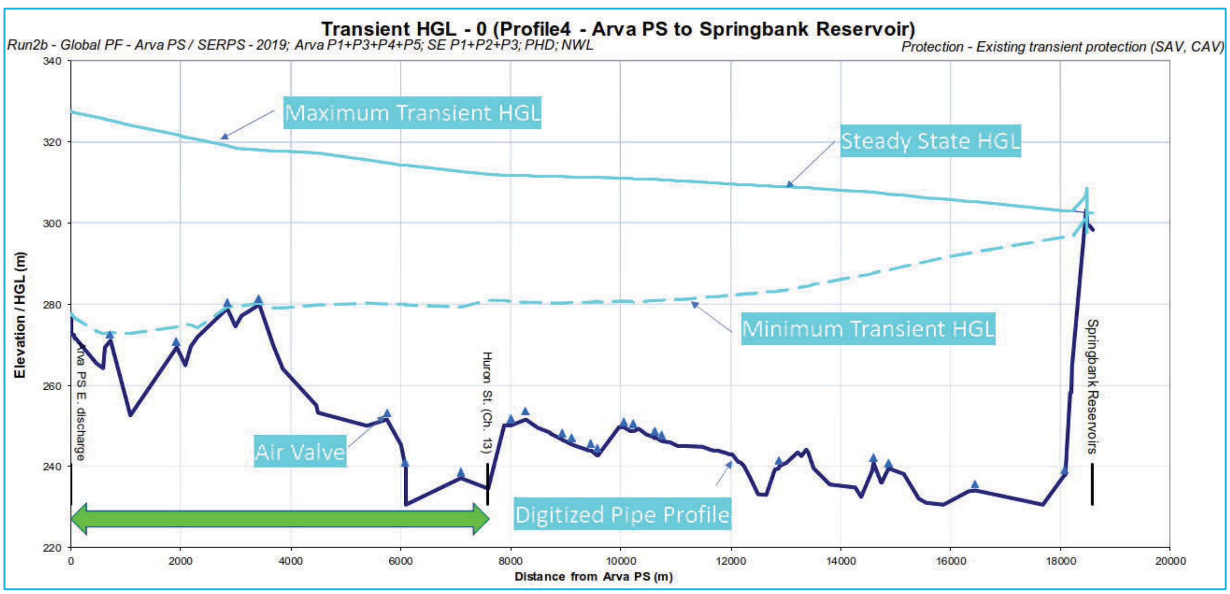


Figure 6: Transient Simulation of Existing Pipe

4.3 Long-Term Actions

The long-term options are those that would occur after 20 or more years. They are mostly related to actions that would extend the service life of the asset such as major rehabilitation or replacement. According to the LoF model developed by Pure Technologies Ltd., no immediate interventions would be required as the minimum range of the RUL was estimated between 20 and 40 years.

For the purpose of this assignment, the strategy will be developed for the next 50 years (until 2070). Although multiple rehabilitation methodologies may be used in the long-term, the replacement action costs are used as they are generally more expensive than rehabilitation methods. Where any future replacements are performed, AFO should be installed.

Based on the LoF results (discussed in **Appendix A**), it is assumed that the section from Windermere Road and Huron Street will be replaced after 30 years (the average of the range) and all other segments would be replaced after 50 years (by that time, the expected service life of PCCP pipelines would have reached or approached their end of service life ~100 years). The approximate replacement cost is shown in Table 16.

Table 16: Replacement Costs

Item	Budgetary Estimate in 2020	Unit	Comments
Replace 1050 mm PCCP Pipe	$9,500	m	Including replacement and engineering services. Costs may differ depending on soil condition and shoring system to be used (if required)

It is important to mention that the LoF assessment completed by Pure Technologies Ltd. was based on several assumptions, which may impact the actual RUL estimates of the segments. The assumptions were as follows:

- Continuous and active deterioration of PCCP sections
- Broken wire wraps were assumed to be contiguous
- EM and AFO inspection data used to estimate the degradation rates
- Yield Limit was considered to be 25 broken wires. The same Yield Limit was applied across the system. However, from the FEA model results (**Appendix B**) and transient analysis (**Appendix D**) where the maximum HGL was estimated to be 119 psi, the Yield Limit would be reached at 35 to 40 broken wires. Therefore, considering the original LoF service life estimations is more likely in the conservative side.
- RUL was estimated from 2018 until the probability of exceeding the Yield Limit reaches 10%

As the consequences of failure and intervention actions for large pipelines are costly when compared to smaller water distribution assets, detailed and accurate engineering analysis would still be essential to minimize the assumptions and conclude RUL of the pipelines at higher accuracies. The detailed engineering analysis would combine:

- AFO monitoring system records
- Recent inspections of electromagnetic tools
- Transient modelling (if operational attributes changed)
- Soil corrosivity results
- Spot assessment results
- Other supporting inputs by the time the engineering analysis is to be performed (e.g. opportunistic assessment)

This detailed engineering analysis would be required after each extensive and comprehensive inspection or monitoring. Approximately, the cost of such an activity would approximately be $150,000 (as per 2020 money value).

4.4 Monetized Strategy

The monetized strategy is built for the next 50 years (up to year 2070) and the following are considered:

- The next soil sampling will be performed every 15 years (in 2035). The strategy considers the collection of at least 10 samples along the watermain within four distinct areas, at various locations within each area as identified below. For reference, the blue line indicates the general watermain alignment and the red circle indicates the potential location to collect the soil samples:

Figure 7: Area 1 – Medway Creek

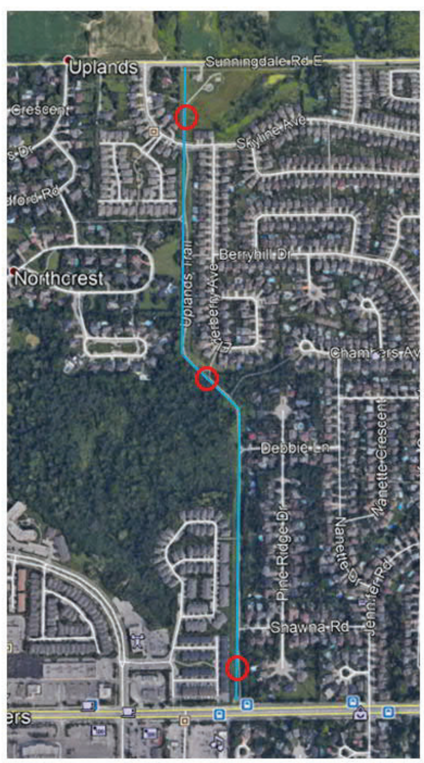


Figure 8: Area 2 – Uplands Trail

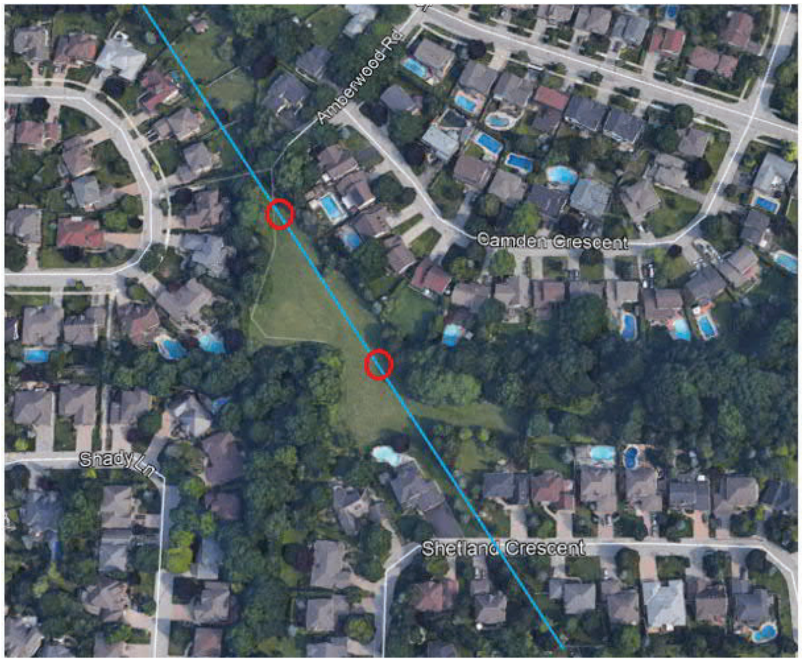


Figure 9: Area 3 – Amberwood Road

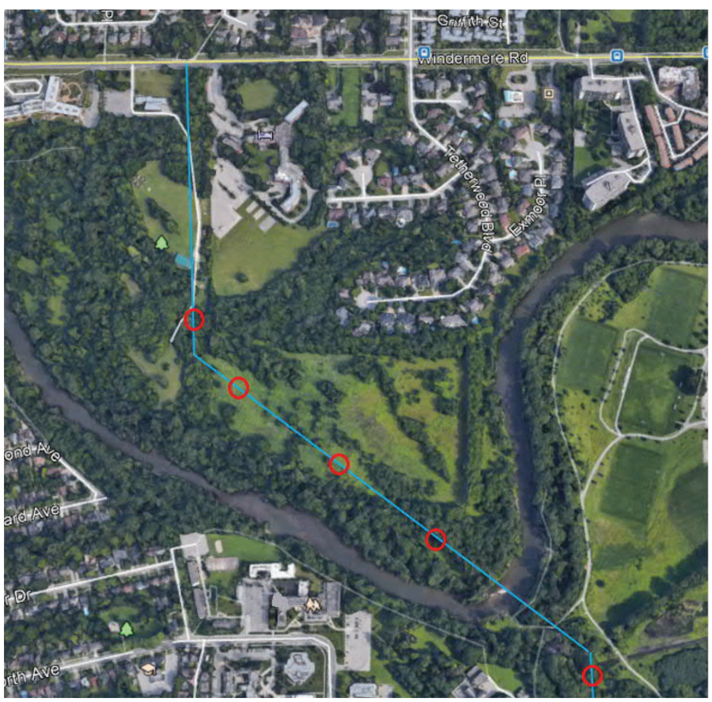


Figure 10: Area 4 – Watermain alignment between Windermere Road and Huron Street

- Test pit locations are determined based on the results of the soil sampling analysis and to be scheduled for 2021 along with detailed engineering analysis and estimate of RUL. The strategy assumes that five test pits are to be considered within each frequency interval and will be based upon the results from the soil sampling analysis, constructability of the test pit, and perceived watermain condition (Table 17).

Table 17: Potential Test Pits Locations

Section	Borehole Location
Windermere Road to Huron Street	Close to BH – E14 Close to BH – E17 Accessible area to the south east of BH-E20
Midway Road to Richmond Street	Close to BH – E1
Fanshawe Parkway Road to Windermere Road	Close to BH - E08

- As EM tools were lately used in 2014-2015, the next EM utilization will occur in 2030.
- In 30 years, the watermain sections from Windermere Road to Huron street may be scheduled for replacement by the end of 2050, and all other sections will be replaced by the end of 2070.
- The six deficient joints where corroding steel was reported in 2007 may be scheduled for repair in 2021 and the remaining six joints to be repaired by 2022.

The overall strategy can be seen in Figure 11 and the breakdown of the calculation is found in **Appendix E**. The bars in Figure 11 represent the future values considering the real interest rate and the budgetary costs in 2020. Based on the cost estimates and the considered long-term and short-term strategies, the PCCP's net present value for monitoring, examining, rehabilitating current deficient joints, and replacing the sections according to their average RUL is around $124 M (the cost of the soil sampling already performed in 2020 are now considered as a sunk cost). Comparing the net present value of the strategy with the "do nothing" consequences ($164 M), the strategy would cost less by approximately $40 M.

This strategy and its associated costs may differ depending on future inspections and analyses (e.g. other joints may be deficient and require repairs). However, the $40 M difference between the "do nothing" and the net present value of the strategy could cover some of these additional costs.

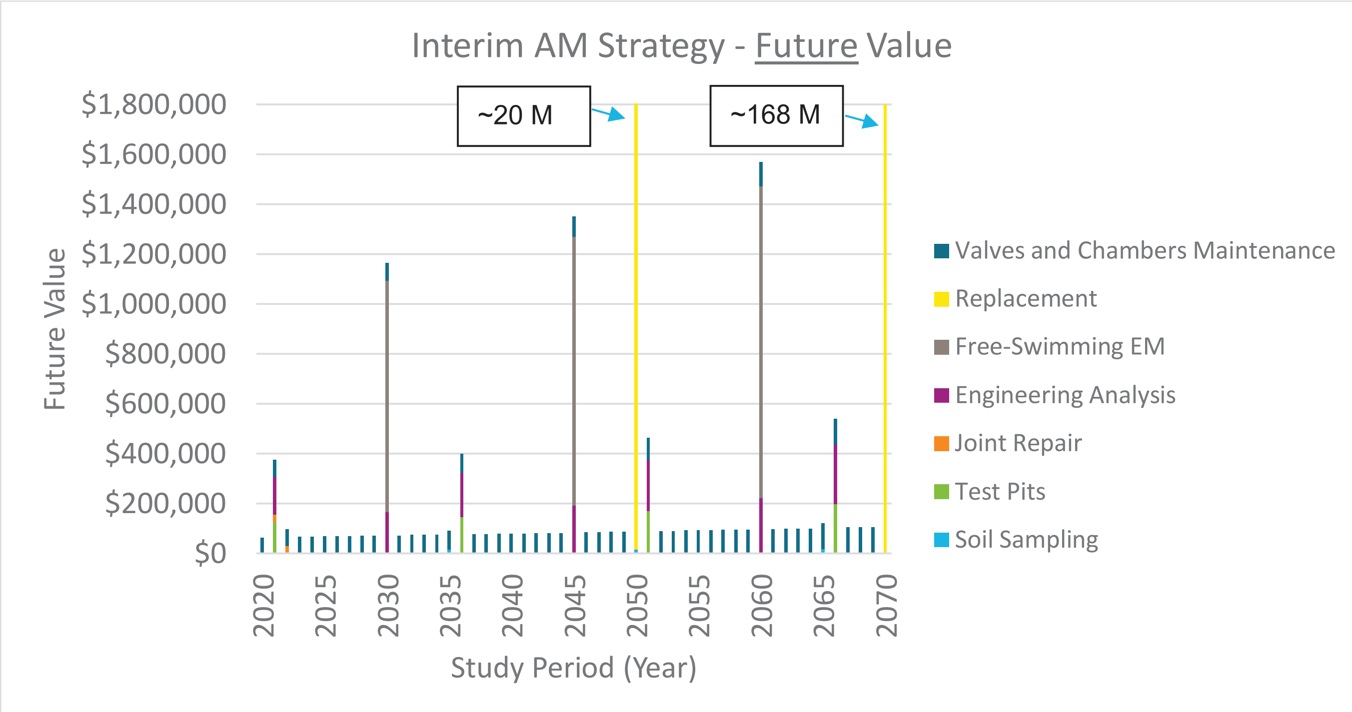


Figure 11: AM Strategy

AECOM Imagine it. Delivered.

Appendix A

Asset Management Review Report

DRAFT

AECOM Imagine it. Delivered.

City of London

Asset Management Review Report: Arva Pumping Station to Huron Street Water Transmission Main Municipal Class Environmental Assessment Master Plan London, Ontario

Prepared by:

AECOM Canada Ltd.
410 250 York Street, Citi Plaza
London, ON N6A 6K2
Canada

T: 519 673 0510
F: 519 673 5975
www.aecom.com

Prepared for:

The Corporation of the City of London
300 Dufferin Avenue
519 661 2489

Date: February, 2020

Project #: 6061950

Distribution List

# Hard Copies	PDF Required	Association / Company Name
1	✓	City of London
1	✓	AECOM Canada Ltd.

Revision History

Rev #	Date	Revised By:	Revision Description
1	05/02/2020	Chris Martire	

AECOM Canada Ltd.
410 – 250 York Street, Citi Plaza
London, ON N6A 6K2
Canada

T: 519 673 0510
F: 519 673 5975
www.aecom.com

Stephen Romano, P.Eng
Environmental Service Engineer - Project Manager
The Corporation of the City of London
300 Dufferin Avenue
519-661-2489

February 10, 2020

Project #
6061950

Dear Mr. Romano

Subject: Asset Management Review Report: Arva Pumping Station to Huron Street Water Transmission Main Municipal Class Environmental Assessment Master Plan London, Ontario

AECOM is pleased to submit this draft entitled "Asset Management Review of Inspections and Risk-Management Framework".

In case you have any questions, please contact the undersigned for more details.

Sincerely,
AECOM Canada Ltd.

Khalid Kaddoura, PhD, PMP, EIT
Project Manager/Asset Management Specialist, Water
khalid.kaddoura@aecom.com

John Hassan, PMP, CET
Senior Vice President
John.hassan@aecom.com

XX:xx
Encl.
cc:

Statement of Qualifications and Limitations

The attached Report (the "Report") has been prepared by AECOM Canada Ltd. ("AECOM") for the benefit of the Client ("Client") in accordance with the agreement between AECOM and Client, including the scope of work detailed therein (the "Agreement").

The information, data, recommendations and conclusions contained in the Report (collectively, the "Information"):

- is subject to the scope, schedule, and other constraints and limitations in the Agreement and the qualifications contained in the Report (the "Limitations");
- represents AECOM's professional judgement in light of the Limitations and industry standards for the preparation of similar reports;
- may be based on information provided to AECOM which has not been independently verified;
- has not been updated since the date of issuance of the Report and its accuracy is limited to the time period and circumstances in which it was collected, processed, made or issued;
- must be read as a whole and sections thereof should not be read out of such context;
- was prepared for the specific purposes described in the Report and the Agreement; and
- in the case of subsurface, environmental or geotechnical conditions, may be based on limited testing and on the assumption that such conditions are uniform and not variable either geographically or over time.

AECOM shall be entitled to rely upon the accuracy and completeness of information that was provided to it and has no obligation to update such information. AECOM accepts no responsibility for any events or circumstances that may have occurred since the date on which the Report was prepared and, in the case of subsurface, environmental or geotechnical conditions, is not responsible for any variability in such conditions, geographically or over time.

AECOM agrees that the Report represents its professional judgement as described above and that the Information has been prepared for the specific purpose and use described in the Report and the Agreement, but AECOM makes no other representations, or any guarantees or warranties whatsoever, whether express or implied, with respect to the Report, the Information or any part thereof.

Without in any way limiting the generality of the foregoing, any estimates or opinions regarding probable construction costs or construction schedule provided by AECOM represent AECOM's professional judgement in light of its experience and the knowledge and information available to it at the time of preparation. Since AECOM has no control over market or economic conditions, prices for construction labour, equipment or materials or bidding procedures, AECOM, its directors, officers and employees are not able to, nor do they, make any representations, warranties or guarantees whatsoever, whether express or implied, with respect to such estimates or opinions, or their variance from actual construction costs or schedules, and accept no responsibility for any loss or damage arising therefrom or in any way related thereto. Persons relying on such estimates or opinions do so at their own risk.

Except (1) as agreed to in writing by AECOM and Client; (2) as required by-law; or (3) to the extent used by governmental reviewing agencies for the purpose of obtaining permits or approvals, the Report and the Information may be used and relied upon only by Client.

AECOM accepts no responsibility, and denies any liability whatsoever, to parties other than Client who may obtain access to the Report or the Information for any injury, loss or damage suffered by such parties arising from their use of, reliance upon, or decisions or actions based on the Report or any of the Information ("improper use of the Report"), except to the extent those parties have obtained the prior written consent of AECOM to use and rely upon the Report and the Information. Any injury, loss or damages arising from improper use of the Report shall be borne by the party making such use.

This Statement of Qualifications and Limitations is attached to and forms part of the Report and any use of the Report is subject to the terms hereof.

AECOM: 2015-04-13

Authors

Report Prepared By: Khalid Kaddoura, PhD, PMP, EIT
Asset Management Specialist

Report Reviewed By: Chris Martire, M.Eng., P.Eng.
Senior Project Manager/Civil Engineer

Table of Contents

List of Figures

List of Tables

Appendices

1. Introduction

1.1 Overview

Generally, transmission mains are considered a critical linear asset in any water network infrastructure (when compared to distribution mains). These pipelines range between 450 mm and above and are made of different material types, including concrete, ferrous, and thermoplastic pipes. However, Pre-Stressed Concrete Cylinder Pipeline (PCCP), a type of concrete pressure pipes, is one of the most utilized type in the industry (American Concrete Pressure Pipe Association [ACPPA], 2012)[1]. This type of material is a complex structure formed by distinct layers of materials (pre-stressing wires, steel cylinder, mortar coating, and concrete core).

In general, limited maintenance/monitoring activities would reduce the remaining service life of the asset and may result in sudden failures, especially in corrosive environment. The failure of PCCP is disastrous and the impacts of its failure would affect the four main pillars (operational, economic, social, and environmental). As a result, proper asset management methodologies need to be present to monitor and maintain transmission mains to attain their expected performance for a better infrastructure.

The City of London retained AECOM to perform a Municipal Class Environmental Assessment Master Plan (EAMP) of a twinned 1050 mm PCCP from Arva Pumping Station to Fanshawe Park and a single 1050 mm between Fanshawe Park Road and Huron Street (Figure 1). As part of this assessment, the City is interested in conducting an asset management strategy of the same pipelines to preserve their performance during their service lives. The asset management scope includes a review of the available inspections and results and a short- and long-term asset management decision variables.

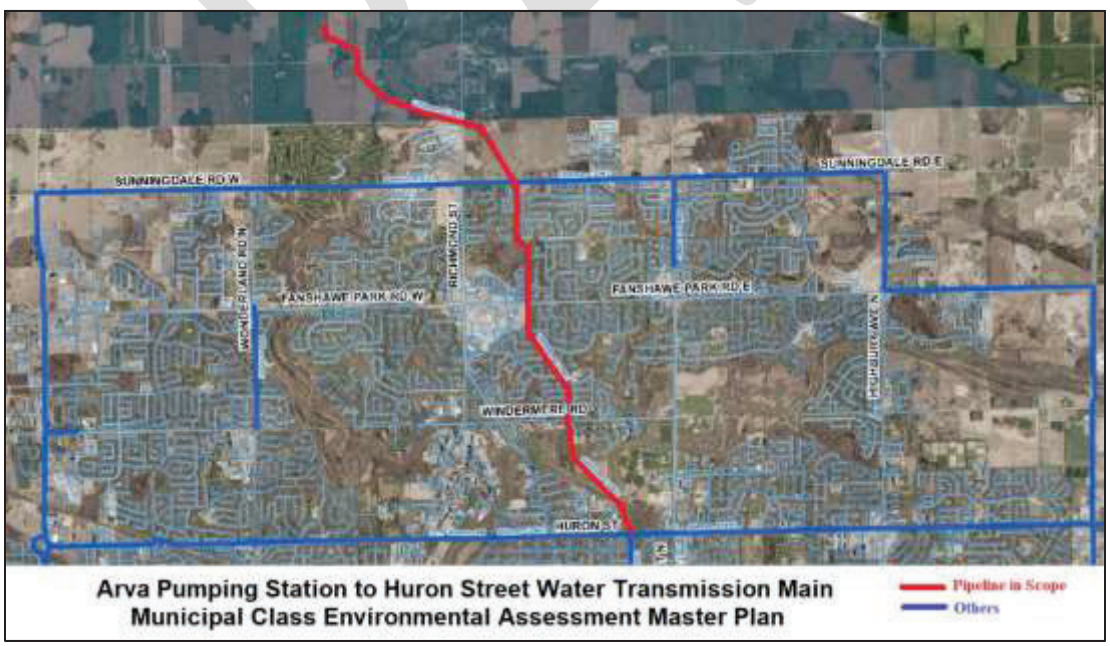


Figure 1: Arva Pumping Station to Huron EAMP PCCP Pipelines

[1] *ACPPA. (2012). "What is CPP?". < http://acppa.org/what-is-cpp/>*

1.2 Report Objectives

The City of London performed several inspections using Pure Technologies' tools to understand the physical and structural state of the asset. In addition, the City of London acquired Pure Technologies to develop a risk-based management framework for large diameter water mains.

This report includes the requirements specified in AECOM's proposal (*Task 2.5 – Asset Management Condition and Needs Confirmation*):

- Review and identify deterioration drivers related to PCCP failures
- Review old and recent condition assessment inspections
- Review and document the existing and recent risk-management framework to identify/confirm critical sections

Based on this review, AECOM will recommend short- and long-term interventions aimed at preserving PCCP pipelines under this scope.

2. PCCP Pipe Types and Deterioration Drivers

2.1 PCCP Types

As per Pure Technologies (2014)[2], the two types of PCCP from Arva Pumping Station to Huron Street are made of Lined Cylinder Pipe (LCP) and Embedded Cylinder Pipe (ECP). Each of these two types has four main components which are the mortar coating, prestressing wire, steel cylinder, and the concrete core. In general, ECP's wires are wrapped on the outer concrete core and that the steel cylinder is embedded between the inner and the outer concrete cores (see Figure 2). LCP has wires wrapped on the steel cylinder and covered with an outer coating (see Figure 3). In ECP and LCP, the prestressing wires place the steel cylinder and concrete cores in compression to sustain the applied loads on the pipe.

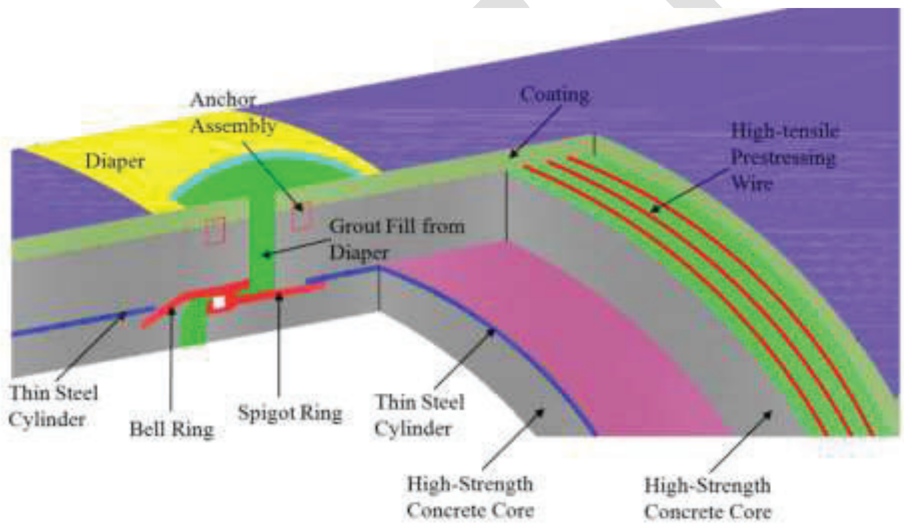


Figure 2: ECP Structure adapted from Ge and Sinha (2014)[3]

[2] *Pure Technologies. (2014). Pipe Diver and SmartBall Inspection: Arva Pumping Station to Spring Reservoir.*
[3] *Ge, S. and Sinha, S. (2014). "Failure Analysis, Condition Assessment Technologies, and Performance Prediction of Prestressed Concrete Cylinder Pipe (PCCP): A State-of-the-Art Literature Review." Journal of Performance of Constructed Facilities*

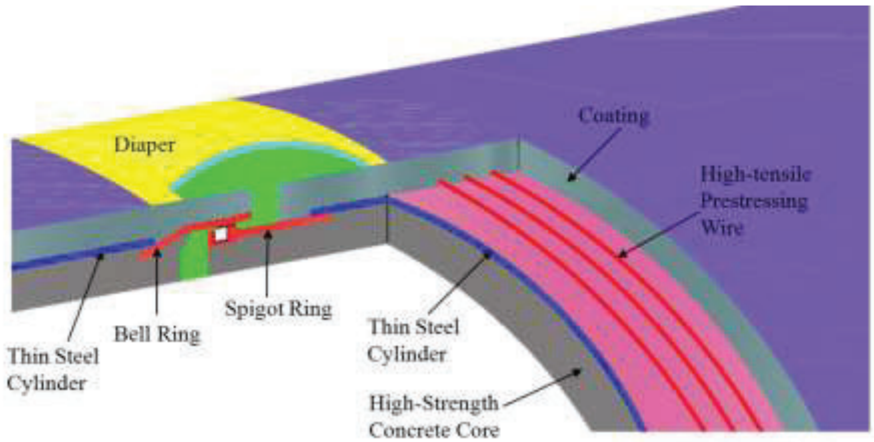


Figure 3: LCP Structure adapted from Ge and Sinha (2014)

2.2 Typical PCCP Deterioration Drivers

As PCCP is a larger diameter pipe usually deployed in critical service, many of its failures are high consequence failures from both a cost perspective and the impact on overall system operation. When design, manufactured, and installed correctly with respect to the applied loads on the pipe and matched correctly to its exposure environment, it can be expected to be a very durable material and have a design life well in excess of 100 years. However, the pipe is a complex composite material made of both ferrous metals and cementitious materials and is susceptible to active deterioration processes if adverse exposure conditions are present and the pipe design is not modified to match those conditions. While PCCP can fail in variety of combinations of root cause, considerable insight into the ramifications of failure risk can be ascertained by understanding the primary modes of pipe failure.

The three primary modes of failure of PCCP are discussed in the proceeding sections.

2.2.1 Failure of the Pipe Barrel

Failure of the pipe barrel is the most catastrophic form of failure. The root cause of barrel failures is prestressing wire corrosion, which occurs when multiple wires corrode to failure and create broken wire zones (BWZ's) along the pipe. When BWZ's become too large, there is a loss of compression in the concrete core of the pipe, which leads to catastrophic failure. Failures of this nature are usually sudden and lead to a large loss of water in a short period of time. A well-documented failure of this nature (full barrel rupture due to excessive BWZ's) occurred in Calgary, AB in 2004 (see Figure 4). This is by far the most serious failure mode and inevitably result in very high direct costs for repair and high consequential damage costs.

In water service, the most common cause of prestressing wire corrosion is a breakdown of the exterior mortar coating due to poor quality control in original manufacture, a bad match of exterior mortar properties and the external exposure environment, or some combination of the two. The high wrapping stresses of PCCP wire are particularly vulnerable to accelerated corrosion as they facilitate stress corrosion cells. As corrosion product develops, it promotes a breakdown of the exterior mortar coating which facilitate further corrosion and an increase BWZ area.

Figure 4: PCCP Barrel Failure - McKnight Blvd and Resultant Loss of Water, Calgary, AB

2.2.2 Failure of the Steel Joint Rings

The corrosion protection for the joint is a field applied grout. In many instances, the grout at the joint preferentially breaks down, either due to poor quality grout being used (it is a field mix), improper installation technique, a bad match of grout properties to the external exposure environment, or some combination of these factors.

Previous investigations by AECOM in Luck Lake, SK (2006-2010) examined and rehabilitated numerous joint related failures on approximately 160 km of PCCP installations. In Luck Lake, the soil chemistry had very high sulphate levels, a fluctuating groundwater table and a mortar grout that was preferentially broken down at the joints due to the external exposure environment and improper grout selection for the exposure conditions. These progressive failures at the joint provided considerable insight into how the corrosion process is advanced once the steel joint rings are exposed to the environment. A typical failure is depicted in Figure 5.

Figure 5: Failed PCCP Joint in Luck Lake, SK

The Luck Lake joint failures typically had the following progression:

In Luck Lake, all joint leaks appeared prior to having extreme BWZ's open up on the pipe. The significance of this is that the failures, while costly and with some consequential damage, never progressed to the stage of a PCCP barrel failure which is a far more catastrophic mode of pipe failure that releases a much larger volume of water upon failure.

Figure 6: Luck Lake, SK - Progression of Joint Deterioration to Prestressing Wires

2.2.3 Failures of the Steel Cylinder

Welding the joint rings reduces the ability of the pipe to articulate at joints. The failure risk associated with the practice is usually limited to inducing a circumferential crack and a leak if excessive joint movement occurs as welding at the joint transfer the bending moment to the steel cylinder which is very thin and will readily crack in bending. This type of failure rarely goes un-noticed as the water loss is usually immediate (the role of the cylinder is to maintain hydrostatic integrity in the barrel of the pipe) and the damage is related to the length of time in responding as extensive water loss can increase the amount of localized damage that occurs. The risk of damage from a cylinder failure can be greatly reduced by simply installing a wide band internal compression seal over the welded joint. The induced moment on the cylinder from joint movement at a welded joint is inevitably very close to the weld and in previous repairs of this type of failures (Winnipeg, MB -2006; Edmonton, AB – 2017); a wide band compression seal (e.g. a Weko-Seal) was used to repair the cylinder failure.

3. Review of Condition Assessment and Risk Management

3.1 History of Inspections

Since 2010, several inspections were performed using several tools including acoustic and electromagnetic technologies in the City of London. As per Table 1, Acoustic Fiber Optics (AFO) were installed since 2010-2012 and PipeDiver (PD) and SmartBall were used in 2014 in inspecting the PCCP sections from Arva Pumping Station to Springbank Reservoir. However, based on “London Arva to Springbank Draft Inspection Report Pure”, SmartBall was not performed on the sections from Arva Pumping Station to Huron Street. Therefore, there is no information related to leak inspection for the scope presented in Figure 1.

Furthermore, calibration testing and validation of inspections were also completed on different pipeline sections including Florence Street Watermain, Sarnia Road Watermain, Commissioners Road Watermain, and Arva Pumping Station to Huron Street Pipeline. Along Arva Pumping Station to Huron Street, two pipes (Pipe 1490 and 1492) between chamber 11 and 12 were removed in 2017 and EM results were validated.

Table 1: Pipeline Condition Assessment History

Inspection Year	Pipeline	Inspection Tool	Material	Total Inspection Distance
AFO System Installed 2010-2012; Currently monitoring	Water Mains from Arva Pumping Station to Commissioners & Wharncliffe	AFO[1]	PCCP	15.8 km
2014	Water Mains from Arva Pumping Station to Springbank Reservoir	PD[2], SB[3]	PCCP & BWP	27.0 km
2015	Hyde Park Water Main	ROB[4]	PCCP & Steel	3.8 km
2015	Sarnia Road Water Main	PD, ROB, SB	BWP & PCCP	6.3 km
2016	Sunningdale Road Water Main	PD, SB	PCCP	8.1 km
2019	Dingman Drive Water Main & White Oak Road Water Main	ROB	PCCP & BWP	2.4 km

3.2 Wire Break History

This section demonstrates the wire break frequency as per the “London Arva PS to Chamber 12A Wire Break_20200110.xlsx” and other related data received from Pure Technologies. **Appendix A** includes many of Pure Technologies’ reports used in analyzing the reported *Wire Break History*.

In the “Pipe Chart” sheet, the number of wire breaks is reported based on Electromagnetic (EM) (PipeWalker and PipeDiver) and AFO. According to the EM inspections, nine pipes experienced wire breaks where the total counts was 69. However, in “EM Wire Breaks” sheet, two additional pipes were reported with each having 10 wire breaks (Pipe # 12A-61 and 12A-63).

Further, AECOM received “Distressed_Pipes_in_Valley_Image.pdf” (**Appendix B**) that contained some chainages of the observed distressed pipes with PipeDiver information and the revised results through PipeWalker inspection. After comparing the “London Arva PS to Chamber 12A Wire Break_20200110.xlsx” with the “Distressed_Pipes_in_Valley_Image.pdf”, two observations, using external inspection, were missing in the excel file at Start Chainages 224+55 and 224+87, where 23 and 42 wire breaks were reported, respectively. The same Start Chainages represent Pipes 11-170A (Pipe# 1490) and 11-170C (Pipe# 1492).

Through the review, it has been observed that the same two pipes were removed in December 2017 (as reported in Electromagnetic Calibration and Validation Report in 2019) and the results of the PipeWalker and PipeDiver were validated. Following the removal of the mortar to expose the prestressing wires, 16 broken wires were observed in 11-170A and 21 broken wires observed in 11-170C. It is believed that these pipes were replaced with newer sections and therefore no wire breaks were reported in “Pipe Chart”. Nevertheless, this should be confirmed as “Pipe Chart” lacked any information of any replacement.

By combining the counts, the total wire breaks from EM inspection was 89. It is important to note that some of the PipeDiver inspection results in 2014 were revised in 2015 by using the external inspection.

In the “AFO Wire Breaks” worksheet, there were 28 reported wire breaks in 23 pipes. The records of the frequency commenced in 2011 (baseline of wire breaks) until 2019. As the total wire breaks exceeded the number of pipes, some pipes experienced more than one break during the monitoring period (2011-2019). Figure 7 shows a histogram of the wire breaks occurrence from 2011 to 2019. As per the figure, most of the wire breaks occurred in 2013 (seven wire breaks). Roughly and on average, three wire breaks occurred in a year. Figure 8 shows the frequency of the wire breaks per Pipe ID. Most of the identified pipes experienced one wire break from 2011 to 2019; however, four wire breaks from 2012 to 2015 were detected in Pipe 11-182 (one wire break a year).

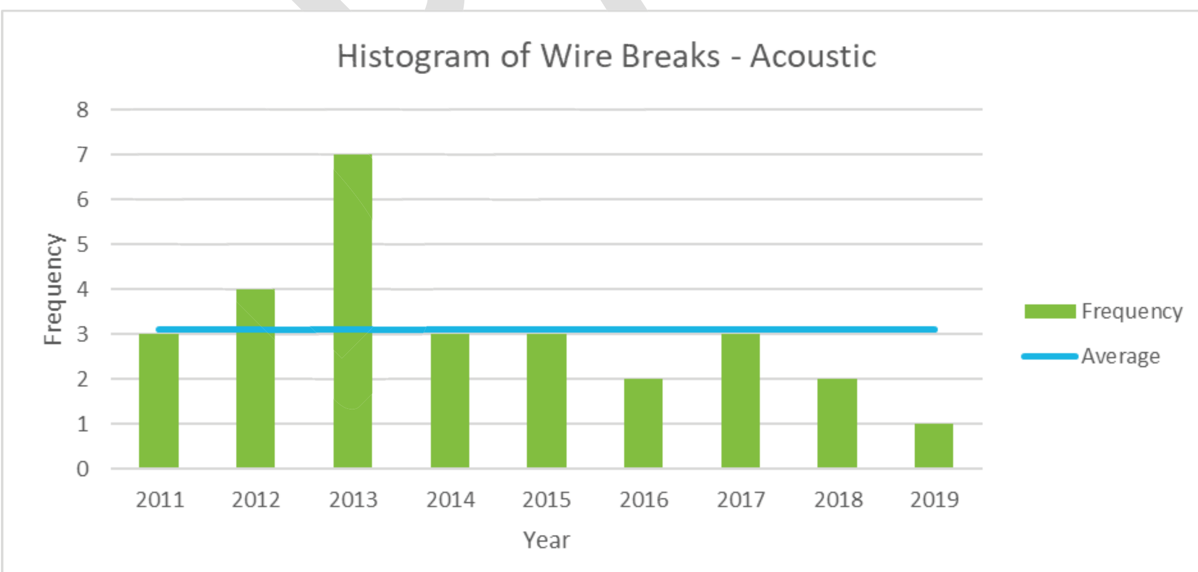


Figure 7: Histogram of Wire Breaks – Acoustic Sensors

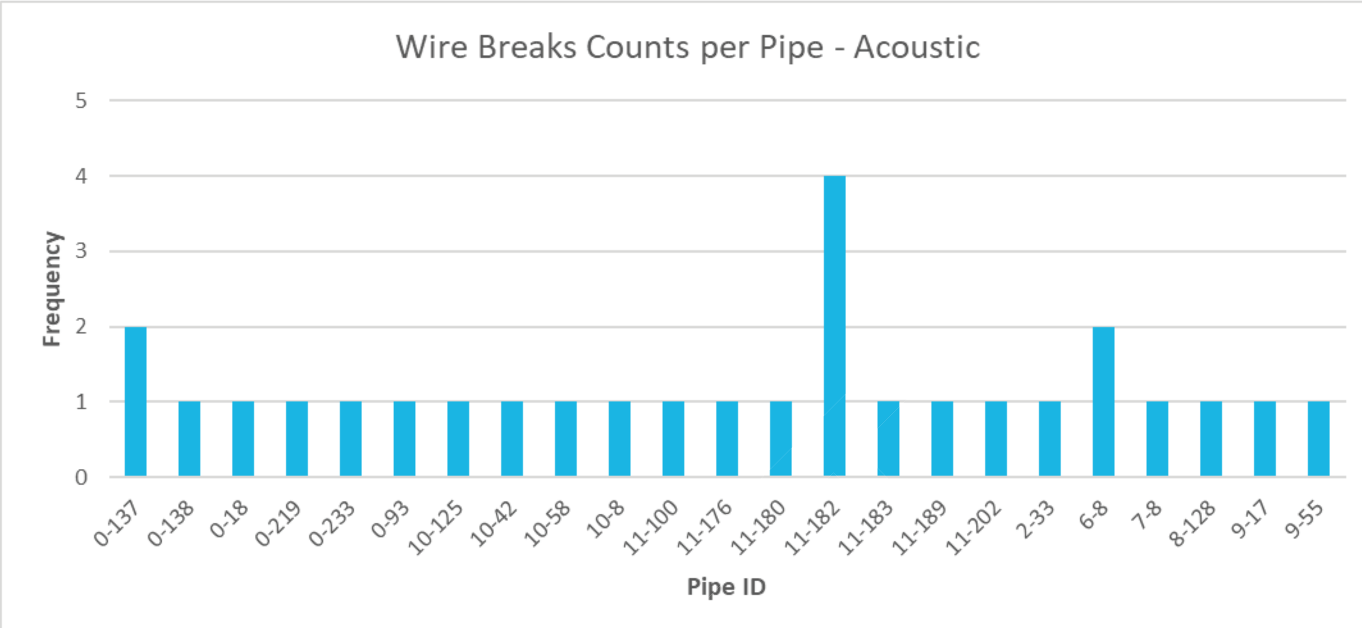


Figure 8: Histogram of Wire Breaks per Pipe ID – Acoustic Sensors

The information from AFO and EM inspections were integrated in Figure 9. The y-axis represents the wire break frequency and the x-axis denotes the start chainage of each Pipe ID. The figure suggests that 14 pipes with reported wire breaks are located from Start Chainage 213+33 to 229+41, in which 9 distressed pipes are within 500 m (Start Chainage 222+95 to 227+34). This figure excludes Pipe# 1490 and 1492 as it is expected that these pipes were replaced once they were removed for validation.

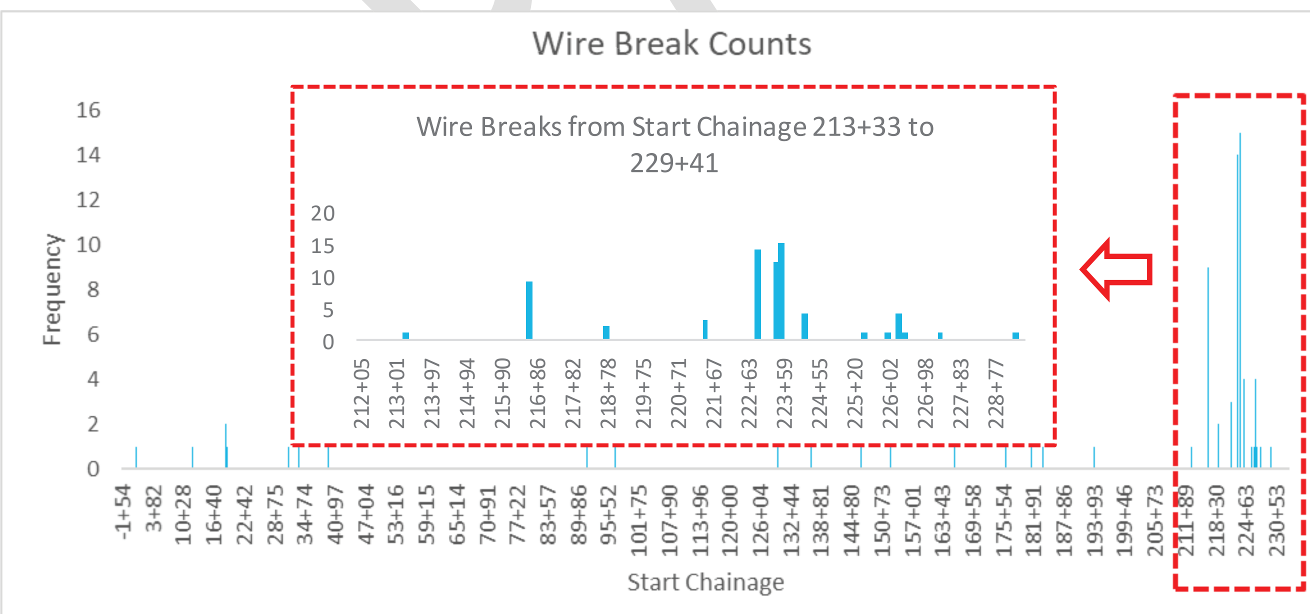


Figure 9: Wire Break Frequency – Acoustic and EM

Pure provided the MS Excel file, "London Arva PS to Chamber 12A wire break history_20200110.xlsx", to AECOM on January 13, 2020 summarizes the accumulated wire break data. The EM Wire Breaks worksheet includes two readings of 10 wire breaks on pipe number 12A-61 and 12A-63 (station location not provided) inspected with the PipeDiver in September 2014. The same readings are not included in the worksheet labelled "Pipe Chart" which includes wire break information along the pipeline from AFO, PipeDiver, and PipeWalker external scanning tool. The same worksheet includes seven of the nine distressed pipes inspected in December 2015, where pipe number 11-170A (station 224+55) and 11-172 (station 224+87) are not identified.

Figure 7 shows the wire breaks detected by AFO in each year. According to Figure 7, 14 different pipe sections experienced at least one wire break during 2011 and 2013. It was expected that wire break information for the pipes reported for the PipeDiver inspection in 2014 (assuming that EM inspection was conducted where AFO is installed) would be included. However, this information is not found in the "Pipe Chart" worksheet. Furthermore, the same two pipes (11-170A and 11-172) were removed in December 2017, where the mortar was removed on both pipes. Also, pipe specification measurements of the exposed prestressing wire were taken and Pure conducted continuity tests. However, this event is not identified in the "Pipe Chart" worksheet. Following the removal of the mortar, to expose the prestressing wires, 16 broken wires were observed in 11-170A and 21 broken wires observed in 11-172. Pure conducted previous investigations of inspected PCCP within the City and determined a Suitable Yield Limit to be 25 broken wire wraps. This is consistent with the average of Pure's EM/AFO database with PCCP confirmed with similar characteristics. It is important to note that this investigation/review is not representative of a structural analysis. The original PipeDiver and external scanning results were reviewed against wire measurements collected by Pure to confirm the calibration curve used to quantity the quantity of broken wire wraps.

The calibration curve used for the Arva Pumping Station to Huron Street pipeline is a suitable choice; however, it does not exactly match the pipeline specifications. The results of the continuity testing compared to the external electromagnetic data yielded a higher number of wire breaks when compared to the continuity testing results. This is due to the location and scattered spacing of the wire breaks which can lead to an overestimation of the quantity of wire breaks.

3.3 Risk-Management Framework

Pure Technologies completed a risk-management framework for large pipeline diameter in 2019 (**Appendix A**). The risk model consisted of the two risk parameters which were the Likelihood of Failure (LoF) and the Consequence of Failure (CoF) as shown in Figure 10.

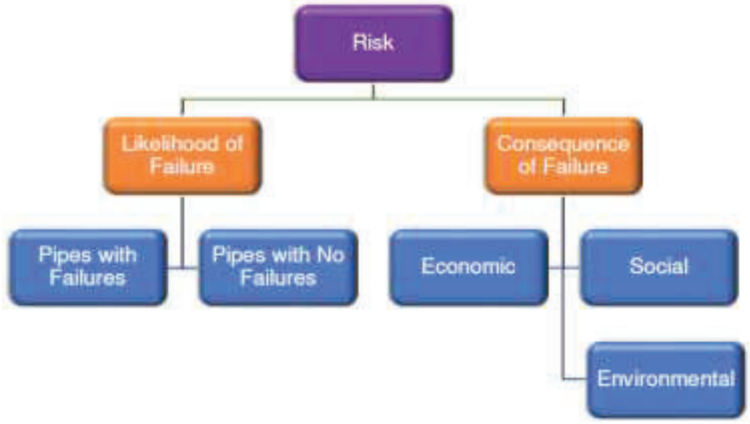


Figure 10: Pure Technologies Overall Risk Framework

3.3.1 Likelihood of Failure

The Likelihood of Failure (LoF) score ranged between 1 to 5 and was based on the City's condition rating chart. The score relied on the break records for large water mains, condition assessment results, and the estimated Remaining Useful Life (RUL) of the pipes. According to the report, the RUL estimates were based on a discussion between Pure and the City (see Table 2).

Table 2: Pure Technologies LoF Definition

Score	Summary	City of London Definition	RUL Definition
1	Very Good Fit for the future	The infrastructure in the system or network is generally in very good condition, typically new or recently rehabilitated. A few elements show general signs of deterioration that require attention.	RUL > 60 years
2	Good Adequate for now	The infrastructure in the system or network is in good condition; some elements show general signs of deterioration that require attention. A few elements exhibit significant deficiencies.	40< RUL <= 60 years
3	Fair Requires attention	The infrastructure in the system or network is in fair condition; it shows general signs of deterioration and requires attention. Some elements exhibit significant deficiencies.	20< RUL <= 40 years
4	Poor At risk	The infrastructure in the system or network is in poor condition and mostly below standard, with many elements approaching the end of their service life. A large portion of the system exhibits significant deterioration.	0< RUL <= 20 years and/or pipes with any breaks
5	Very Poor Unfit for sustained service	The infrastructure in the system or network is in unacceptable condition with widespread signs of advanced deterioration. Many components in the system exhibit signs of imminent failure, which is affecting service.	RUL <= 0 years and/or multiple pipe breaks in last 5 years

Pipes that experienced multiple breaks in the last five years were directly assigned a score of 5 whereas pipes had a one break were assigned a score of 4. Based on this discrete assignment, 19 out of 770 segments were assigned a score of 4 with no pipes with a score of 5.

Further, the RUL values were estimated to determine the LoF values for pipes. Pure considered several assumptions to perform this calculation, including:

- Continuous and active deterioration of PCCP sections
- Broken wire wraps are assumed to be contiguous
- Electromagnetic and AFO inspection data used to estimate the degradation rates
- Yield Limit was considered to be 25 broken wires. The same Yield Limit was applied across the system
- RUL was estimated from 2018 until the probability of exceeding the Yield Limit reaches 10%

The RUL was estimated based on the following steps:

1. Develop deterioration cases – In the order of five broken wire wraps
2. Fit distributions – Distributions per case and installation periods were generated. The best fit in all cases was determined to be exponential.
3. Utilize Monte Carlo Simulation to estimate levels of distress over the next 60 years
4. Determine RUL
5. Determine LoF score

Based on Pure's methodology, the representative LoF map is shown in Figure 11. The LoF of Pipes from Arva Pumping Station to Windermere Road ranged between Very Good (RUL is greater than 60 years) to Good (RUL is between 40 to 60 years) and the segment located to the south of Windermere Road to Huron Street is ranked as Adequate (RUL is between 20 and 40 years).

Figure 11: LoF Map

3.3.2 Consequence of Failure

The approach monetized the impacts of large diameter failures based on social, economic and environmental impacts. The following factors were considered:

Social Impacts:

- Impact for affected customer (Level of Service) – it was calculated considering residential and non-residential areas
- Property damage – it considered the structure and contents damages
- Road traffic disruption – considered the expected traffic delays
- Railway disruption

Economic Impact:

- Replacement costs – it considered the cost of replacing large pipes

Environmental Impact

Based on the aforementioned factors and subfactors, the consequence model generated the results shown in Figure 12. As per the figure, the CoF for pipelines stretching from Arva Pumping Station to Huron Street were between less than $2 M and greater than $50 M. None of the sections along this stretch were between $10 M and $20 M. From the visual representation, slightly more than half of these transmission mains' CoF was in the $2 M and $10 M.

Figure 12: CoF Map

3.3.3 Risk Management Review and Analysis

- The structural analysis of the pipes under AECOM's scope were not available at the time of Pure's LoF estimation. Pure assumed the Yield Limit to be 25 broken wire wraps in which the actual analyses may conclude a different number.
- The LoF ranks were predominantly in the Good range. The segment from the Windermere Road to Huron Street was in an Adequate condition.
- The CoF of the PCCP pipe with an Adequate condition was in the fourth CoF rank (cost of failure was estimated between $20 M and $50 M)
- The most critical section (based on CoF value) was the segment from Fanshawe Park Road to Windermere Road. The same segment's LoF was Good.

The two most critical sections of the Arva Pumping Station to Huron Street pipeline are the segments located between Fanshawe Park Road and Windermere Road (Red, CoF > $50 million) and Windermere Road to Huron Street (Orange, CoF of $20 – $50 million). The pipeline crosses Fanshawe Park Road East through an easement that runs between Masonville Square and 58 Fanshawe Park Road East. This pipeline runs through residential properties of the Masonville area, where it crosses Windermere Road between 531 Windermere Road and the Ivey Spencer Leadership Centre. Based on the monetized approach that Pure followed, the CoF for this section is appropriately graded due the high social and economic impacts if failed.

The second critical section is the one that runs East of 531 Windermere and heads south through the ravine area of North Branch Park crosses underneath the Thames River. It also passes through the forested areas east of the London Campus of the International Centre for English Academic Preparation and Merrymount Family Support and Crisis Centre. The CoF for this section is appropriately graded due to its social impacts, resulting from adjacent residential properties. The grade also includes the environmental failure impacts due to its location within the vicinity of Thames River. The two most distressed pipe sections, as per Pure's analysis, were removed from this region in December 2017.

The remaining pipe sections from Fanshawe Park Road East to the Arva Pumping Station have lower CoF grades (<$2 million). This is due to the pipeline's minimal social and environmental impacts compared to other large sections in the network.

4. Conclusion

The PCCP deterioration drivers attributed to failure of the pipe barrel, steel joint rings and the steel cylinder, are associated with the likelihood of failure. Most often, failure of one or more of these identified components results in increased social, environmental, and economic costs.

The assessment of the 1050 mm PCCP watermain from the Arva Pumping Station to Huron Street is based on the electromagnetic inspection data compiled by Pure Technologies and associated risk framework used to classify the watermain sections in terms of their likelihood and consequence of failure. Pure assumed 25 broken wire wraps within a pipe section and applied that rationale in support of the remaining useful life of a pipe section. The watermain sections aligned between Windermere Road and Huron Street has highest estimated likelihood of failure, between 20 and 40 years, based on the quantity of wire breaks within the nine sequential pipe sections between chamber 11 and chamber 12. The watermain sections located between Fanshawe Park Road and Windermere Road has the highest consequence of failure as it is aligned throughout several residential properties. The second highest section is aligned through a vegetated ravine area adjacent to the Thames River which poses an environmental impact in the event of a failure within this area. The approach that provides the most value to the City is to consider the identified PCCP watermain sections with the highest likelihood of failure and the highest consequence of failure in future planning and developments to mitigate these estimated risks.

5. Recommendations

The following recommendations are presented for the City's consideration:

- Pure Technologies to compile and resubmit the wire break data and associated parameters and make reference to the pipe sections removed December 2017.
- Since the soil type and its resistivity provide insights whether the surrounding environment is corrosive or not, it is recommended to perform a soil corrosivity testing along the critical sections (Fanshawe Park Road East to Huron Street). The analysis of the soil sample would include tests of sulphide, chloride content, sulphate, pH, electrical conductivity, resistivity, redox potential, and moisture index. Based on these results, the Corrosivity Index would be calculated as per AWWA C105. According to the total length of the critical section, 15 to 20 samples would be required.

Contact

Neil Awde, P.Eng
Senior Project Manager
T +519 963 5885
E neil.awde@aecom.com

John Hassan, PMP, CET
Senior Vice President
T +519 963 5889
E john.hassan@aecom.com

aecom.com

Contact

Neil Awde, P.Eng
Senior Project Manager
T +519 963 5885
E neil.awde@aecom.com

John Hassan, PMP, CET
Senior Vice President
T +519 963 5889
E john.hassan@aecom.com

aecom.com