CANADIAN MUNICIPALITY WATER MAIN CONDITION ASSESSMENT AND PIPE RENEWAL METHODS

By

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Abstract

In general, there are two types of pipe renewal methods, replacement and rehabilitation. Replacement methods is where pipes are replaced with new ones using original open-cut methods, or trenchless technologies such as pipe bursting and auger boring; while rehabilitation methods repair pipes by installing smaller pipes or liners inside the old pipe using technologies such as CIPP, spray-on lining, slip lining, etc. The market for rehabilitation of water infrastructure has been growing rapidly due to the increasing volume of aging underground utilities in urban centres. The implementation of trenchless rehabilitation method for underground pipe renewal can improve construction efficiency and significantly decrease project costs compared to open cut methods. Trenchless technologies provide a much faster repair time, and consequently reduces the crew size and cost in built-up city areas where open-cut methods are more difficult to perform (Hashemi et al., 2011).

While trenchless rehabilitation methods have been generally directed towards gravity sewers, it is important to dedicate resources to understand the application of these techniques to water main. The loss of valuable drinking water due to leaking pipes results in the loss of billions of dollars around the world each year (Rogers, 2014). However, it is more complex and challenging problem to rehabilitate water mains in comparison with gravity mains. This is due to several reasons. First, for water mains, rehabilitation product used must be safe for drinking water delivery. Secondly, the rehabilitation process must result in a system that is capable of withstanding high internal operating pressures and pressure surges.

In order to understand the challenge with rehabilitation of water mains, comprehensive understanding of existing water main in terms of overall system condition, degree of deterioration

of different pipe material, and characteristics of water mains will need to be performed. With this information, the rehabilitation method conducted on the water mains can then be further improved through better planning and more effective product for different water main pipe materials or circumstances. To gather the information, an online survey questionnaire was conducted to collect data on municipal water main conditions as well as methods used for pipe renewal. First of all, information on pipe diameter, buried depth, as well as lengths are gathered with respect to pipe diameters distinguishing between transmission and distribution. Furthermore, information related to service connection, including the years that certain materials were used, and methods for establishing connections to water mains were collected. Meanwhile, another important aspect addressed in the survey is the pipe failure rating/factor for different materials. This information allows water providers and those involved in water main rehabilitation to understand the performance of various materials within the system and plan appropriate mitigations. Lastly, the condition assessment methods employed by the surveyed water utility providers are summarized. Also, replacement and rehabilitation methods used previously for system pipe renewal are examined and compared.

CIPP can provide structural support to both internal and external loads, while spray-on techniques provide chemical resistance as well as adding minor strength to the existing pipe, but theoretically will not be able to withstand surrounding structural loads. Current existing CIPP liner products for pressurized water-pipes are designed and installed using the same standards as for gravity mains with low internal pressure consideration. The full review of the current gravity main product and installation standard are presented in the body of this thesis. The current methods have been safely applied in the industry following the water rehabilitation manual M28 (AWWA), as well as adapting knowledge and experience from past projects. However, the development of standards

specifically for application of CIPP to rehabilitate pressurized water mains is very important as pressurized water mains will experience high internal pressure with pressure surge occurring throughout the system, such that the current design standard are not sufficiently developed for their application on pressurized water mains.

Furthermore, there is a high potential for expanding the industry by increasing the knowledge about the equipment and skill set for this type of water main rehabilitation. The current major market for CIPP products and the history of the development of trenchless rehabilitation technology are discussed, as well as current methodologies. Furthermore, the design, installation, and monitoring of current water main rehabilitation products are discussed, where the associated risks or limitations are described. Also, outline of existing standard tests for main rehabilitation are included as part of the evaluation of existing products and procedures, improvements and future research topics are also suggested.

Preface:

This thesis is an original work by Yichen Wu. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Survey Questionnaire on Water Main Rehabilitation", No. Pro00085656, December 7, 2018.

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Chapter 1: Introduction

1.1 Background

Urbanization of populated areas has been rapidly increasing over the past half century. It has been predicted that the urban populations will grow and reach 66% of the total global population by 2050 (United Nations, 2014), which represents approximately 2.5 billion additional people in cities. To support the fast-growing urban population, the demand for efficient water and wastewater services will also escalate. Currently, most buried underground utility distribution systems have been aging and deteriorating since the time of their first installation in the early 19^{th} century (Hughes et al., 2011). As of 2018, most existing pipe utilities around the world will be over 50 years old (CFM, 2016) and their condition will continue to deteriorate over time. Eventually, issues such as pipe blockage, leaks, and poor water quality will emerge over time (Grigg, 2005), raising concerns in terms of economy, environment, and social impact. These issues, however, can be mitigated at an early stage with well-established condition assessment programs and appropriate rehabilitation methods.

With the aging of potable, waste, and storm water utilities, municipal governments have growing concerns regarding the possible health and safety risks their systems pose to citizens, including poor water quality, and leakage causing sinkholes on the roads. In fact, a survey conducted by Canadian Municipal Asset Management Assessed the current condition of Canada’s water infrastructure and found that approximately 12% of its systems are in poor or very poor condition and require immediate maintenance (CFM, 2016). Meanwhile, 20% are in fair condition, which indicates no immediate threats (CFM, 2016); however, close monitoring and renewal are suggested to prevent potential pipe failures. In addition, these studies have indicated that by investing early in restoring the pipe conditions, the rate of pipe deterioration and long-term repair cost can both be reduced significantly (CFM, 2016). In Canada, an estimated $60 billion should be spent on immediate water infrastructure replacement or rehabilitation over a 10-year time period, according to the Canadian Infrastructure Report Card (CFM, 2016). Conversely, for pipes in fair condition, the replacement value was estimated to be $100 billion. These values suggest a large amount of construction work will be forthcoming in the water utility rehabilitation industry. Therefore, the selection of appropriate methods for rehabilitation or replacement will be essential in providing cost effective construction to save the capital budget for municipal governments, which will ultimately benefit citizens (Zhao and Rajani, 2002).

It is important to gain an understanding of the condition of various pipe materials within water distribution/ transmission systems and assess water systems before the system get to the point when pipes begin to deteriorate (CFM, 2016). Water main rehabilitation has not been-prioritized until recent years, when governments realized that existing water utilities lose up to an estimated 40% of drinking water through current distribution systems (Loiacono and Cote, 2013). These water losses costs way more compared to costs due to damaged sewer mains. In addition, damaged drinking water systems create other issues that eventually require more expenditures to fix. Water main pipe breakages are sometimes associated with the appearance of sinkholes created by soil around the break point being washed away. These sinkholes can destroy infrastructures (i.e. roadways and other structures) if the sinkhole reaches the surface. Sinkholes result in water contamination risk and pose a threat to public health and safety.

1.2 Problem Statement

In the past years, surveys have been conducted by Utah State University for assessing the water main conditions such as failure rating and possible reasons for causing the failures (Folkman, 2018). The past survey results present a good general picture of the municipal water systems in

North America, however, there are many other areas that previous researchers did not consider, such as pipe condition or failure rating/factor for individual materials. Also, another essential part of water system that was overlooked in past surveys is service connection pipes, where very little information was reported.

The material failure study conducted from previous surveys by Utah University did not take pipe diameter and type of water system into consideration (Folkman, 2014, 2018). In the Utah surveys, the factors considered were pipe age, soil type, corrosion prevention technique and climate conditions (Folkman, 2018). Although water main systems mostly consist of distribution systems with pipe diameters between 6 and 12 inches, this does not mean that the failure rating/factor between transmission systems and distribution systems could be different.

Lack of consideration for rehabilitation methods in previous Utah State University's Surveys (Folkman, 2018) is another issue that need to be addressed. The comments from respondents to the survey by Utah State University indicate that CIPP, HDPE and spray-on liners had higher costs compared to open cut methods and were only used when open-cut was not feasible (Folkman, 2018). Furthermore, Folkman (2018) mentioned that rehabilitation methods were only used for large diameter pipes, and many utilities were not happy with the results (Folkman, 2018). This information from the survey conducted by Utah State University is only a very brief summary or responses related to alternatives to open-cut methods, and thus a more in-depth questionnaire would be helpful to compare perceptions about different rehabilitation methods.

1.3 Research Objectives and Scope

The main objectives of this thesis are listed as following.

Objective 1: Perform a thorough literature review on CIPP and Spray-on lining rehabilitation methodologies from design to post installation for both gravity and water main. The history, major marketing, design and installation standards of CIPP and Spray-on rehabilitation technologies will be summarized in detail.

Objective 2: Investigate existing standard and tests which can be applied for monitoring or assessing the condition of the water mains, rehabilitated liner and pipes. Furthermore, the limitation and risks associated with CIPP and spray-on lining, as well as corresponding mitigation plans are discussed.

Objective 3: Understand the characteristics of utility water main, in terms of operating pressure, buried depth, system length, and pipe conditions for different materials. Gain better understanding of water main conditions through condition failure ratings/factors for more insight of the actual performance of water systems for different size of pipes and different pipe materials, to allow utility providers to target on the section of pipes in different systems with higher failure rating/factors and provide early mitigation actions correspondingly.

Objective 4: Investigate water main renewal methods by comparing between replacement and rehabilitation methods in terms of method usage, unit costs, and annual budgets. Also, by analyzing the factors each utility provider considered for selecting pipe renewal method, the results can be used for future project planning and delivery for both rehabilitation and replacement renewal methods.

The preceding objectives will help to improve water providers and rehabilitation industry's understanding of the current water main conditions, such that better water main pipe material can be chosen for future pipe installations. Also, more accurate decisions can be made for future renewal projects in whether to choose rehabilitation or replacement. More importantly, a design standard for water main rehabilitation may be strengthened from the results.

1.4 Research Methodology

In order to meet the objectives identified in the previous section, a comprehensive literature review on previous water main surveys, as well as on rehabilitation of using CIPP and spray-on methods was completed. Also, an online survey questionnaire on water main condition and system characteristics were conducted for data collection and analysis. In order to correlates and support the findings from the survey results on water main conditions as well as pipe renewal methods, past surveys and literatures were reviewed to back up the results. Both the findings from past literature review and the survey will be used to make suggestions to water main industries on which is the better method for pipe renewal.

First of all, to obtain new useful data for research will require research and study of past surveys and literatures on water mains to gather current understanding of the water main conditions and related information. From the past surveys, useful characteristics can be also implemented in this thesis, while new areas of finding or analysis can be employed in improving the area of research. One of the main source of survey looked into was the Utah State University (Folkman, 2018), which conducted data collection throughout United States with various areas looked into such as break rates, pipe materials, water systems distributing the water, cause of water main breaks, as well as corrosion protection and condition assessment of water mains (Folkman, 2018). These surveys conducted previously looked into broader area of the state of water mains, however, more insight of the pipe break rate can be conducted by implementing a more proactive data and analytic analysis similar to the one performed by Grigg in his “Data and Analytics Combat Water Main Failures” (Grigg, 2019). In Grigg’s research, however, most of the analysis was done to the general water main system as well, the detail of pipe material failure was not conducted, as a result, it was an opportunity to conduct a failure factor/rate of the water systems that can look deeper into the data and identify issues within certain pipe range as well as pipe material type.

The online survey questionnaire conducted for this research was prepared using Survey Monkey (an online survey tool) and a pilot version of the survey was sent out to collect data for the purposes of this research. The responses can be used as a steppingstone in improving a future survey that will be sent out to collect more comprehensive data from a wider selection of cities across Canada and North America. The survey contained two sections: the first section covers water main characteristics, while the second section covers water main renewal methods. The online survey questionnaire consists of 24 questions, and are include in Appendix I. The time to answer the questionnaire was expected to be between 25 to 30 minutes to keep the respondent from running out of patient. This online survey was designed and planned to be as concise and short as possible and are targeted for municipality or water utility providers across North America. The questions in the survey were discussed with experienced industrial associates as well as knowledgeable professors from different universities. The survey was approved by the University Of Alberta Board Of Ethics. For the purpose of this thesis, a pilot survey was sent out to six water utility providers in Canada through industrial associate, by sending a survey link through email. Four cities responded to the survey, with the size of the survey questions, the data from four cities will be enough to achieve the objectives.

The purpose of the survey is to help provide more detailed data for water providers to realize the potential issues within their system that has not been recognized in past researches and studies. Also, with the analyzed data of the system condition, proactive renewal action can be made, and suitable method can be selected. The questions within the survey was designed to, first of all, reflect the general characteristics of the system surveyed. The characteristics include information such as length, operating pressures, and buried depths for different water systems. These characteristics are important information to know for analysis and understanding of the condition that the systems are in. As for length, it will be used for calculating the condition failure rating/factor for different pipe material. The failure rating/factor is not time or age based, instead, it is simply assessing the condition of the material at this stage of its life span based on the number of breaks occurred in the past years, as well as the length of the material for a certain size of pipe. The higher failure rating/factor will indicate more issues related to that pipe material under different water distribution and transmission systems. Operating pressure is another important factor to understand for the effect of high internal pressure and pressure surge have on the pipe material condition. Typically, higher the operating pressure in a pipe system will create more constant stress to the pipe especially at where tuberculation occurs due to corrosion. This constant stress will lead to leakage or even pipe bursting. Beside from constant operating pressure, pressure surge due to opening and closing of valves will also result in changing the flow inside the water main from laminate flow to turbulent flow creating stress to the internal surface of the pipe. In addition, data regarding the buried depth or the cover depth of the system will help to indicate any possible correlation between the water main conditions and the depth it was buried. Although the pipes must be buried below frost line based on different city season temperatures, however, the soil pressure will induce certain level of external pressure that may affect the condition of the pipe.

The second portion of the survey questions (Q6 – Q15) was designed to collect more detailed information into different size of water systems and different pipe material types. In collaboration, the data should help provide an overall picture of the condition of the water systems but will also be used to calculate the condition failure rating/factor for more insight of the actual performance of water systems for different size of pipe and different materials. The data required to calculate the condition failure rating/factor are water mains material percentage for different systems, break percentage for various materials, water main system conditions, as well as number of breaks occurred in the past year. It is a simple step to evaluate the city's overall performance using a failure rating/factor (Table 10), which is simply using the total number of breaks occurred in the past year to divide by the total length of water systems. The numbers will indicate if a city's overall condition is acceptable or not, yet, it will not reflect the actual details. In order to fully understand the breakdown of the conditions of pipe, the following steps will be used to obtain the failure rating/factor for materials in different pipe system or size.

1. *Length of Different Systems (Figure 1) x Material Percentage of Water Mains (Table 5) = Length of respective material under different system*
2. *Break Percentage for Different Material (Table 10) x Total No. of Breaks Occurred in Past Year (Table 10) = No. of Breaks Each Material Type Occurred in Different Water Systems*
3. $\frac{No.\ of\ Breaks\ Each\ Material\ Type\ Occurred\ in\ Different\ Water\ Systems}{Length\ of\ Respective\ Material\ Under\ Different\ System} = Failure\ Factor$

The analyzed results are the most important findings from the surveyed data sets, where both the methodology and results will be useful for water utility providers and related industries. Additionally, service connection is also an important part of the overall water systems, yet, very limited research and data collections was performed previously. As a result, the questions related to service connections is also included to reflect part of the overall water system.

The third and last portion of the survey is to obtain data related to the quality control and quality assessment as well as unit cost, length repaired, and annual budget for system renewal programs. This information will be useful to determine the future prosperity of methods in maintaining the quality of water mains. With the unit cost and the length repaired values, the annual cost for both rehabilitation and replacement can be compared with respect to past one year, two years and five years. The money saved using one type of method can be a good suggestion for utility company to choose the cheaper method in future pipe renewal projects. Also, the cost different between past cost and future annual budget can also be analyzed in order to indicate the change of preference in renewal methods. Although, in reality, the decision to make the choice in the construction type for renewal can be complicated depend on many factors. Therefore, one of the survey questions was to ask the water utility provider to rank their impression of the factors that are most important to least important while making decision in which method to choose for construction.

These methodology and analysis have been well thought and refined hundreds of times into the 24 questions. Initially there were fifty questions that are expecting detailed answers, which is a time-consuming process that will eventually scare away respondents. As a result, many questions were combined and changed so the questions can easily be answered with accuracy in a short time. The survey was designed and modified based on past literature researches, as well as getting comments from experienced technical personnel. However, there still are many improvements that can be made based on the responses from the survey participants. The findings from the survey is highlighted at the conclusion of this thesis.

With the results collected and analyzed through survey, the results can be supported with previous surveyed data, however, to recommend on the side of choosing pipe renewal methods, more literature review on rehabilitation will have to be performed. As in the current water industry, pipe renewal using open-cut and other replacement methods has been well developed and used around world, but rehabilitation methods such as CIPP and spray-on methods are mostly used for sewer pipe or gravity main pipes instead of water main. Therefore, literature review on CIPP and spray on rehabilitation methods was performed to illustrate the advantage and disadvantage compared to replacement methods. The history, major marketing companies, design and installation standards of CIPP and Spray-on rehabilitation technologies was looked into to reflect the basic characteristics of these methods. Furthermore, research in the existing standard and quality assessment/quality control methods or tests that can be applied for monitoring and assessing the condition of the water mains after installation. To better compare with replacement and open cut methods, limitation and risks associated with CIPP and spray-on lining, as well as corresponding mitigation plans are discussed to reflect if implementing rehabilitation methods will be a good trade-off for renewing water mains.

1.5 Thesis Structure

The entire thesis consists of a total of seven chapters. A brief description of each chapter is given below.

Chapter 1: Provide brief background on issues related with current municipality water main infrastructures. State the problem related with water mains that this thesis is based upon. List the objectives that this thesis is trying to convey to the reader, then provide the methodology used to achieve the objectives. Describe each component of the thesis.

Chapter 2: Introduce the practical advantage of using rehabilitation methods in contrast with open-cut replacement method. In addition, slip lining, CIPP and spray-on methods of rehabilitation were compared. The differences between rehabilitation of gravity sanitary sewer and pressurized water mains will also be identified.

Chapter 3: Illustrate results based on data collected through online survey questionnaire. The conditions of existing water mains in different cities will be identified, including the failure factor of breakage for different materials and systems. Water loss, service connections, and other characteristics of the water main systems will be summarized and compared between the surveyed cites. The surveyed data are compared with literature reviewed results from previous surveys conducted by Utah University.

Chapter 4: The results of analyzed data from the online survey questionnaire regarding condition assessment are summarized. The unit cost, length repaired, and annual budget for rehabilitation or replacement methods for previous water main renewal projects were also collected and analyzed.

Chapter 5: Perform thorough literature review on CIPP and Spray-on rehabilitation methodologies from design to post installation. Suggest reasons for choosing these two rehabilitation methods as a good alternative for replacement methods based on literature review. The detailed historical development on water main rehabilitation products and processes are discussed. The geo-marketing of the major industrial companies and their products will also be described. Furthermore, existing standard and manual for product design and installation procedures will be listed and defined. Description on CIPP and Spray-on field installation process will be included.

Chapter 6: Investigate the existing standard and tests which can be applied for monitoring or assessing the condition of water mains or rehabilitated liner and pipes. Furthermore, challenges and risks associated with CIPP and spray-on are listed and discussed. Possible mitigation actions are analyzed and listed. Additionally, challenges and issues related to rehabilitation of pressurized water mains will be identified, along with potential mitigation methods. Also, appropriate monitoring methods are recommended.

Chapter 7: Conclusions are made based on results from previous chapters. In addition, potential areas for future research are suggested to further improve the product and design methods for rehabilitation of water mains using trenchless technologies.

Chapter 2: Literature Review of Previous Work

Water main systems is being widely built throughout present world, not only in populated areas, but rural areas as well. These systems provide great accessibility to the users, yet, it is the utility provider's responsibility to ensure their water mains are in adequate conditions to safely and cost effectively in providing its citizens with everyday use of water. Most of the first installed water mains have been in service about 50 years in North America (Folkman, 2018). With the aging and deterioration of the pipes, issues related with water main breaks have been the major concern for utility providers. When a water main fails, cost is not the only issue that arises, for instance, environmental impact as well as social consequences also need to be dealt with.

2.1 Conventional Open-Cut vs Trenchless Construction

In general, there are two approaches that can be used in dealing with pipe deterioration and breakage, proactive or reactive approaches (Grigg, 2019). The reactive approach is most commonly used by water utility providers, such that whenever a break occurs or noticeable pipe failure has been observed, a pipe rehabilitation or replacement method will be implemented. A proactive approach is when utilities apply early analysis of system condition to anticipate and mitigate main failure before it could actually happen (Grigg, 2019). As suggested by Grigg, effective data base analysis supports utilities in early identification of issues and providing an enhanced overall water main condition (Grigg, 2019). However, many utilities are currently trying to improve their technologies in terms of condition assessment and monitoring, while data analytics were rarely implemented for water main assessment (Butler, 2017). In this context, methods for water main renewal need to be determined and executed. The most typical, standard method of replacing or renewing underground utilities has been to carry out open trench construction work. This is a difficult process, especially in populated areas, as concentrated structures and facilities above ground are inevitable. Most often, open trenching increases the capital cost of projects, creates inconvenience to the public, and in some cases is hard or impossible to carry out (Wassam, 2015). Deployment of trenchless technologies, on the other hand, greatly benefits the rehabilitation process of underground utilities and brings value to all parties by providing safer work conditions, lowers project costs relative to open-trench methods, creates less environmental impact, and these technologies are more efficient and productive than conventional open cut methods (Hashemi et al., 2011). Safer working conditions are achieved, since in most cases equipment is sent underground instead of people. Also, as construction is more efficient and productive, the construction process involves less crew hours and downtime, which consequently results in a decreased carbon footprint and lower project costs (Beale et al., 2013). In general, open trenching is more practical and cost efficient for projects in shallow conditions (S. Apeldoorn, 2010). However, for projects that are deeper or located in dense areas, the cost reduction of trenchless technology compared to conventional open cut methods can range from 20% to 60% (R. Mohammad et al., 2008). Trenchless technologies began to be developed in the late 20th century and were considered to be innovative technologies at the time. After almost four decades of improvement and innovation, trenchless construction is currently applied for underground construction projects in countries all around the world. In addition, the technologies have been evolving in its applications in different areas and for different purposes, including, for instance, pilot tube micro-tunnelling (PTMT), which is used for installation of new underground pipes. Tunnel boring machines (TBM) is used for tunneling, while pipe bursting is used for old pipe replacement. On the other hand, the cured-in-place-pipe (CIPP) and spray-on lining are used for pipe rehabilitation. These diverse underground construction technologies have helped to improve the efficiency of the underground construction industry and provide benefits to public health and safety (Bontus, 2008).

2.2 Trenchless Replacement Methods vs Rehabilitation Methods

There are generally two approaches to underground pipe renewal. One approach is where the pipe diameter is increased by using the pipe bursting method for installation, which replaces old pipes with new ones that have same or larger diameters (Hashemi et al., 2011). Another approach involves lining the existing pipe, which decreases the internal diameter of the pipe, but provides enhanced service conditions, as well as a degree of structural stability to the pipe. This second approach includes techniques such as CIPP, slip lining, and spray-on cement mortar or epoxy. Cement mortar was the first method developed in the early 1900s, while slip lining was developed later in the 1950s (Kozman, 2013). Both of these techniques are early innovations prior to CIPP and spray-on. Cement mortar involves application of cement to the inside of the pipe to provide a new internal surface. In slip lining, new pipe is inserted into old pipe and the annular gap space is filled with grout for sealing and bonding. Currently, slip lining is only advantageous in the case of renovation for medium to large sewer pipes (Hashemi et al, 2011), as by-passing is not required for most sewer utilities.

If the construction area is restrained, such as when the utilities are below crowded and congested residential areas, then both pipe bursting and slip lining will be more disruptive compared to CIPP or spray-on due to the large access area required for construction (Hashemi et al, 2011). CIPP and spray-on methods would then be the more suitable solution, since the set-up equipment requires very little space above ground (Lanzo Lining Services, 2010). Additionally, open cut is required where service connections are located for both pipe bursting and slip lining methods, which results in a significant increase in work and cost (Hashemi et al, 2011). Using CIPP, however, service connections can be reinstated internally after installation by employing robots and closed-circuit television (CCTV) equipment. At the moment, after decades of advancement, CIPP has become the most popular method for rehabilitation of water infrastructure due to its fast installation and easy access in limited space (Sterling et al., 2009). Nonetheless, research on the design standards for rehabilitation of water mains has been falling far behind on the development of rehabilitation technologies. The design has to account for high pressure and pressure surge within the operating pipe, as well as the monitoring of rehabilitated mains.

For trenchless rehabilitation methods, aside from CIPP lining method, which provides semi-structural to fully structural rehabilitation of pipes, there is also the spray-on lining technique. When an aging pipe has cracks and defects, it does not only results in water leakage, but could also allow heavy metals from the surrounding soil and the corroded host pipe to leach into drinking water (Ellison et al., 2010). Spray-on cement mortar or epoxy may be effective to provide a coating on the internal surface of the pipe that prevents further corrosion and biofilm tuberculation of the host pipe, in turn maintaining a safe potable water delivery system (Ellison et al., 2010). However, it is applicable only if the host pipe is assessed to be structurally sustainable for another long period of time, since spray-on lining is currently designated as a non-structural solution. Epoxy has a strength of its own, such that if a thick layer of the product is applied, support to the existing structure for a short period of time is achievable; however, this solution is costly compared to CIPP rehabilitation (Bontus, Personal Communication, 2019). Also, long term deformation and safety aspects will not be guaranteed (Ellison et al., 2010). Up to the present, polymer spray-on lining method has been widely applied for distribution water main systems with diameter between 6” to 12” and proven to be beneficial in many cases. One of the benefits of spray-on lining is fast installation times, even compared to CIPP. For spray-on lining, a one-day construction period and service bypassing can be avoided (Ellison et al., 2010). In addition, the effort required for service reinstatement for spray-on method is much less compared to CIPP, since suction or blowing of air from the service pipes can easily remove the thin film of polymer that covers the service connections (Ellison et al., 2010).

Trenchless rehabilitation methods have been applied to both sewer (gravity main) and pressurized water (force main) pipes, however, the development of product and installation methods for sewers is way ahead of water mains. For wastewater systems, most of the issues and challenges were encountered and resolved at the current stage, the design standard of rehabilitation of sewer pipes also has been well developed to provide quality rehabilitation product design. In contrast, issues and challenges that came across water main system has not yet been fully resolved, where the pipe condition of existing water mains has not been fully elaborated (CFM, 2016) with limited knowledge on condition of water mains. Also, design standard of rehabilitation of water mains still require expansion that take into consideration high pressure and pressure surge. Table 1 compares the challenges for rehabilitation projects for both water mains and sewer mains and indicates whether or not the challenge has been resolved.

Table 1. CIPP Installation Requirements Comparison between Gravity Main and Water Main Systems

Challenges	Gravity main		Water Main		Comments
	Required?	Resolved?	Required?	Resolved?	
Cleaning	√	Yes	√	Yes	
Service By-Pass & Pumping	√	Yes	√	Yes	Expensive step
Excavation of Access Pits	N/A	N/A	√	Yes	Currently unavoidable for water mains
Service Connection Reinstatement	N/A	N/A	√	Yes	May require external service reconnection
Disinfection	N/A	N/A	√	Yes	
Product NFS/ANSI 61 Requirement	N/A	N/A	√	Yes	Only four products were approved
Approved Design Standards	√	Yes	√	No	Partial for water main
Low Pressure Consideration	√	Yes	√	Yes	Current water main pressure design uses the same design method as for gravity mains
High Pressure Consideration	N/A	N/A	√	No	
Surge Pressure Consideration	N/A	N/A	√	No	

The challenge with water main rehabilitation using CIPP requires more consideration than rehabilitation of sewers. First of all, access for sewer pipe rehabilitation can be achieved through available manholes, whereas water mains require excavation of access pits for installation. Therefore, water main lines have to be shut off, and service by-passing needs to be in place to ensure regular water delivery to surrounding communities (Allouche et al., 2014). In addition, sewer infrastructure is often larger in diameter, which may allow enough space for the technician or construction personnel to access the inside for walkthroughs and checkups before and after installation (Allouche et al., 2011). However, water main pipes are generally smaller in diameter and inspection most often relies solely on CCTV equipment. In cases where water pipes have severe tuberculation inside, the smallest inspection equipment may not even be able to get past those locations. A more prominent issue is that the availability of water main CIPP products is limited, as lining products for potable water pipes must not cause long term health effects, and disinfection after installation must meet local regulatory requirements. The standard NSF/ANSI 61 is most often applied. Furthermore, water mains are also a pressurized system and the design of the CIPP product needs to withstand high internal pressures with surge cycles.

Chapter 3: Canadian Municipalities Water Main Condition

3.1 Introduction

Surveys on water main were conducted previously to collect data for analysis, which is considered as a tool for asset management for water utilities (Folkman, 2018). The objective of the surveys, however, did not focus on areas such as methods of condition assessment and monitoring, nor on water main rehabilitation or replacement methods. The goal of the current survey was to form a database that not only focuses on the pipe properties of various water utilities, but also is beneficial in providing a better understanding of municipal water conditions and the characteristics of different pipe renewal methods. To accomplish this, an online survey questionnaire was designed (APPENDIX A) and sent out to six participants from different Canadian water utility providers, as municipalities are the owner of the data instead of local regulatory. Four participants responded to the pilot version of the survey.

The survey was designed to collect comprehensive data, while minimizing the time spent on the survey. The questions were carefully designed and prepared such that a limited number of questions were required for participants to answer. Also, to save time for participants, most of the questions were set up as multiple choices with values or range of values for respondents to choose from. Furthermore, based on discussion with experienced engineers and industrial partners, for the purpose to collect meaningful information and achieve the objectives of this thesis, data was collected for three ranges of pipe. One range category is the distribution system with pipe diameter between 6 inches to 12 inches. The other two categories are transmission systems with pipe diameters from 12 inches to 24 inches, as well as greater than 24 inches.

3.2 Municipal Water Main General Information

The basic information collected through the survey questionnaire on the four cities in Canada are described and compared in this section. City A, B, C and D will be used in this thesis, with the city population given for context. Through Figure 1 and Tables 3 and 4, the lengths of different water systems in different cities, operating pressures, as well as their depth are obtained based on the responded perceptions of municipality representative participants. Based on this information gathered, the distinctive characteristics of each city's water system can be clarified, which provides a general overall impression of the system in Canada.

3.2.1 Surveyed City Sizes

The estimated population and size of the surveyed cities are summarized in Table 2. Most often, the utility providers are the municipalities themselves, but not in all cases. Some cities' services are provided by large utility companies. From the table, City B clearly has the largest population size, and is categorized as a metropolitan city. City A and D have similar population size and are both considered large cities and as imminent metropolitans. City C is a medium sized city with less population. It was observed that the length of the respective cities' water system increases based on population magnitude.

Table 2. City Size and Population

Cities	**City A**	**City B**	**City C**	**City D**
City Category	Large City	Metropolitan	Medium Sized City	Large City
Population	~ 1.5 Million	~ 3 Million	~ 600000 - 800000	~1.4 Million

3.2.2 Water System Lengths

The lengths of water systems surveyed for four different cities are shown below in the chart in Figure 1. It is obvious that the majority of the system in all cities are distribution system with diameters from 6 inches to 12 inches. Furthermore, city with larger population has a longer water system as expected. In general, all four cities consist of approximately 80 to 90 percent of distribution systems within their overall water system. Meanwhile, comparing between water transmissions systems with 12 inches to 24 inches pipes, and pipes larger than 24 inches, the lengths are comparable in each city.

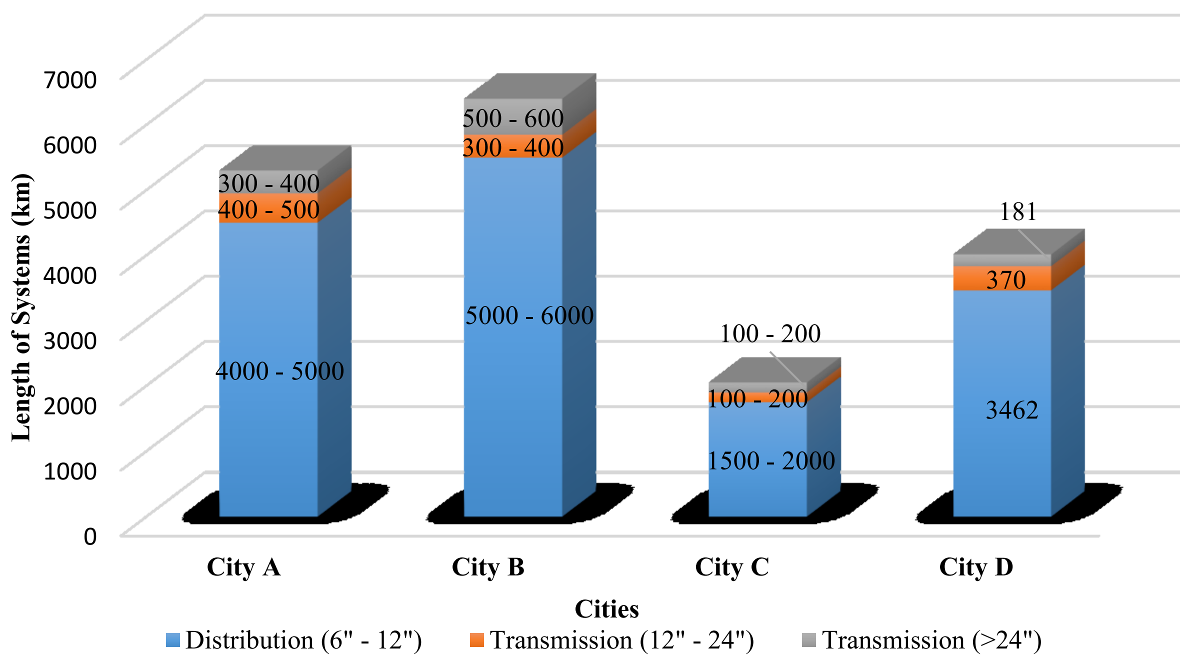

Figure 1. Range of Lengths of Different Water Systems in Different Surveyed Cities

3.2.3 Water System Operating Pressure

In order to deliver water to all the customers, utility providers have to apply continuous pressure to their systems. The operating pressure is therefore an essential factor to be considered while designing and planning for the water main rehabilitation systems. Table 3 below summarizes the collected data on the operating pressures for the four Canadian cities. In general, the operating pressure is higher for larger transmission pipes with diameter greater than 24 inches. City C responded to have the same operating pressure range for all their systems, while Cities A and B both have higher pressure for their transmission system greater than 24 inches. City D has a very large pressure range for their systems; however, the high end of the pressure may be the maximum water pressure or surge pressure, which occurs when pumps start, or a valve is opened or closed in the system. The survey conducted by Utah State University in 2018 on North American water mains reported an average operating pressure of 69 psi or 475 kPa, and a maximum pressure of 119 psi, equivalent to 820 kPa (Folkman, 2018). The surveyed four major cities have a comparable average pressure, yet, questions for maximum pressure or pressure surge should be considered separately for future surveys.

Table 3. Operating Pressures of Water Mains in Different Cities

	System	**City A**	**City B**	**City C**	**City D**
Reported Operating Pressure (kPa)	**Distribution (6" - 12")**	500 - 550	425 - 500	425 - 500	350 - 900
	Transmission (12" - 24")	500 - 550	425 - 500		350 - 1100
	Transmission (>24")	Over 700	600 - 650		350 - 1200

3.2.4 Water System Buried Depth

The depth of buried water mains varies in different cities. The standard cover depth in most areas is approximately 1.5 to 2m based on many municipal design and construction standards in Canada (CFM, 2016). The response from the city representatives in Table 4 indicate a similar range of buried depth, while City A has a deeper cover depth that could be due to the geographical location of the city. For cities with cold winters, the frost depth is much deeper than cities with warmer winters. Such that if the buried pipe is above the frost line depth, a very high chance of freezing pipe will occur in the winter. This will result in unsuccessful delivery of water in these areas and will also result in high possibility of pipe burst or breakage (Cohen, 1979).

Table 4. Water System Cover Depth in Different Cities

	Systems	**City A**	**City B**	**City C**	**City D**
Depth of Cover (m)	**Distribution (6" - 12")**		1.8 - 2.1		1.0 – 1.5
	Transmission (12" - 24")	2.7 - 3.0	1.8 - 2.1	1.5 – 1.8	1.0 – 1.5
	Transmission (>24")		2.1 – 2.4		1.0 – 3.0

3.3 Water Main Pipe Material and Conditions

Cast Iron was the pipe material implemented first for underground water mains in supplying water around the world, many other materials have been tested and slowly put into use as alternatives to provide safe, durable, as well as cost effective water system. In North America, nine materials were reportedly being used in the past few decades as shown in Table 5. The material percentages constituted of the four surveyed cities' water pipelines were summarized and compared. Furthermore, the condition of the water mains was evaluated for installed pipe materials based on survey responses in Table 6.

3.3.1 Material Percentages

Different cities use different materials for the water networks, while, certain types of material were implemented more in general compared to others. The data in Table 5, however, the percentages were entered as an estimation, such that minor deviations are expected.

Cast Iron and Polyvinyl Chloride (PVC) material made pipes have a high proportion in distribution systems with diameter between 6 inches to 12 inches, and transmission system with diameter from 12 inches to 24 inches. Cities A and D have their systems both with over 50% of PVC pipes; City B and C consists mostly Cast-Iron pipes in their system. Due to the fact that Cities A and D; Cities B and C, are located in same regions, therefore the percentage of pipe material installed were approximately the same between these cities. Another major pipe material used for water systems between 6 inches to 12 inches are Ductile Iron and Asbestos Cement, these two materials are also part of the older systems that were first installed in the mid-1900s with life span over 50 years. For water transmission systems over 24 inches in diameter, all four cities have Pre-Cast Concrete Pipes (PCCP) as the main pipe material, while Steel is the second most used material in City A and D. The materials that were least used based on the surveyed data are Fiber Reinforced Plastic and High-Density Polyethylene (HDPE) pipes. The reason why these two materials were less recognized by water utilities is because they are more expensive to manufacture compared to most other materials (Folkman, 2018). Overall, the data collected through the four cities have comparable statistics with survey conducted by Utah University, where their researched water mains also recorded a large utilization of Cast Iron, Ductile Iron, PVC, and Asbestos Cement (Folkman, 2018), which confirms the validity of the results of survey within this thesis.

Table 5. Material Percentages of Water Mains in Different Cities

Material (%) & Rating	Distribution System (6" – 12")				Transmission System (12" – 24")				Transmission System (>24")			
	City A	City B	City C	City D	City A	City B	City C	City D	City A	City B	City C	City D
Cast Iron	15%	65%	45%	16%	2%	45%	45%	3%	-	10%	35%	-
Ductile Iron	25%	10%	30%	-	10%	15%	<2%	-	-	<2%	<2%	-
Asbestos Cement	<2%	<2%	-	28%	6%	6%	-	28%	-	-	<2%	-
PVC	55%	20%	25%	56%	60%	15%	30%	50%	4%	-	<2%	6%
HDPE	2%	<2%	-	-	4%	-	-	1%	2%	-	-	2%
Steel	2%	-	-	-	10%	-	4%	10%	25%	-	10%	42%
Fiber Reinforced Plastic	-	-	-	-	-	-	-	1%	-	-	-	2%
PCCP	-	-	-	-	8%	-	20%	7%	70%	85%	45%	48%
Concrete Pipe	-	<2%	-	-	-	20%	-	-	-	6%	-	-

3.3.2 System Conditions

The ratings of pipe materials in Table 6 were collected in this survey to assess the current condition of water mains in Canada. Overall, City A has a relatively better water system out of the four cities, with only Cast Iron pipes in distribution system having a fair condition rating. City B and D on the other hand have comparably lower ratings, where, poor condition was rated for Ductile Iron pipe in City B's distribution system, as well as all Cast Iron pipes for City D. Of all water systems, distribution system has a more concerning rating compared to the transmission systems, which is expected, since the majority of water main network is consisted of distribution system. In term of materials, concerns are mostly related with Cast Iron and Ductile Iron pipes, where most of these two types of pipe material are in fair conditions or lower; while other material are mostly in conditions that are above average. It is important to point out that the ratings are based on individual participant's perception of their municipality water main conditions, it may not reflect the actual true condition of each city's water system. As a result, a more insightful analysis will be performed in Section 3.6 to further illustrate the actual condition for different pipe material with different pipe ranges.

Table 6. System Conditions for Water Mains

Material (%) & Rating	Distribution System (6" – 12")								Transmission System (12" – 24")								Transmission System (>24")							
	City A		City B		City C		City D		City A		City B		City C		City D		City A		City B		City C		City D	
Cast Iron	15%	C	65%	C	45%	B	16%	D	2%	B	45%	B	45%	C	3%	D	-		10%	C	35%	B	-	
Ductile Iron	25%	B	10%	D	30%	B	-		10%	B	15%	C	<2%	B	-	B	-		<2%	C	<2%	B	-	
Asbestos Cement	<2%	B	<2%	B	-	B	28%	B	6%	B	6%		-	C	28%	C	-		-		<2%	C	-	
PVC	55%	A	20%	A	25%	A	56%	A	60%	A	15%	A	30%	A	50%	A	4%	A	-		<2%	B	6%	
HDPE	2%	A	<2%	A	-		-		4%	A	-		-		1%	B	2%	A	-		-		2%	B
Steel	2%	B	-		-				10%	B			4%	B	10%	B	25%	B	-	A	10%	B	42%	B
Fiber Reinforced Plastic	-		-		-		-		-		-		-		1%	B	-		-		-		2%	C
PCCP									8%	B			20%	B	7%	B	70%	B	85%	A	45%	B	48%	B
Concrete Pipe	-		<2%	A	-		-		-		20%		-		-		-		6%	B	-		-	

In 2016, Canadian Infrastructure Report Card reported that 12% of Canadian potable water systems are in poor or very poor conditions, while 20% in fair conditions (CFM, 2016). It is not part of this survey questionnaire to collect percentage of systems under different conditions, however, relatively comparable percentiles of pipe physical conditions were observed from this survey as well.

3.4 Water Main Service Connection

Service connection is an important part of the water main system that have not been focused on in terms of research in the past, while evaluating water mains (Bontus, Personal Communication, 2018). For instance, the material used for service connections, methods used for installation of service connections, as well as service connection current conditions, all have limited information, where this information can be useful when pipes require replacement or repair. By collecting data related to service connection, municipal water providers as well as water rehabilitation or replacement industry will be able to make plans and designs accordingly in different situations.

3.4.1 Service Connection Material Utilization Years

Service connection pipes were initially installed in late 1800s, since then, 5 types of materials were put into use until the present days. Figure 2 below illustrates the timeline of each material used since around 1880s until 2019 for the four surveyed cities. Similar to the trend with water main pipe material percentages, cities in a similar region have relatively alike timeline of material utilization years for service connections. City B and C started using lead as the main service pipe material before 1880s, and was stopped using around 1950s, at which point copper was then introduced and are still being used in the current water system. City A and D first started installing service connection pipes using copper around 1900, and it is still the main material used in the present. During the years1970s to 1980s, City A and D also started implementing PVC pipes, which City B and C did not install for their system. Galvanized pipes were also installed in many cities, where City B used it for the longest period of time, approximately about 100 years. Out of all four surveyed cities, HDPE pipes were implemented only by City A. The information not gathered through this survey, however, is the extent or magnitude of service connection pipe installed for individual material, which can be very useful to include in future surveys.

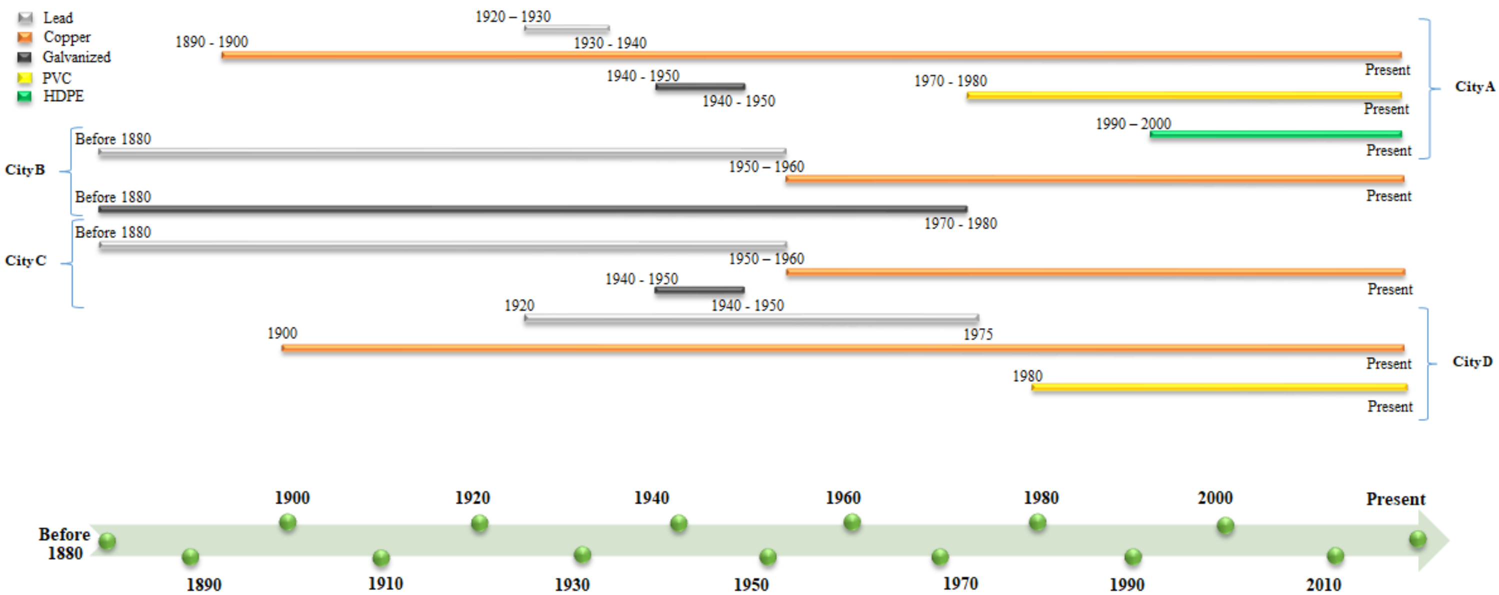

Figure 2. Different Material Utilization Years for Service Connection

In the current water main system, service connection pipes made of lead and galvanized material have been stopped using due to issues raised for these two materials. Lead pipes in water system increases the blood lead level in human body, especially for children (Rabin, 2008). Such that if consumed for a long period of time, lead poisoning will result in fatal illness as well as having permanent effects on mental and physical development of young children (WHO, 2018). Galvanized pipes are steel pipes coated with zinc, with a minimum lead content of 0.5%. After aging and degradation, it can also be a long-term source of lead (Clark, 2015). Furthermore, besides from causing human health issues, the two pipe materials will result in lead building up inside the pipe surface during degradation, which will essentially affect water flow in the system.

3.4.2 Method of Installation for Service Connections

Two main methods used for connecting service pipes to water mains in North America are direct tap and service saddle. The purpose of recording the use of the two methods for different material is to provide reference for rehabilitation industries to have a better understanding of the existing systems, so appropriate improvements for future projects can be made. From Table 7, the methods for installation of service connection onto different material varies from city to city has no recognizable trend in which method is more preferable than another. This may be due to the small sample size collected from the survey. However, one noticeable finding is that direct tap method has been major method used on cast iron water mains pipes service connections for the three cities who responded to this question.

Table 7. Percentage of Service Connection Methods Used on Different Water Main Pipe Materials

Material (%)	City A		City B		City C		City D	
	Direct Tap	Service Saddle	Direct Tap	Service Saddle	Direct Tap	Service Saddle	Direct Tap	Service Saddle
Cast Iron	80% – 90%	10% - 20%	N/A		80% - 90%	10% - 20%	95%	5%
Ductile Iron	5% – 10%	95% - 100%			80%	20%	95%	5%
Asbestos Cement	10% – 20%	80% – 90%			-	-	95%	5%
PVC	95% - 100%	0% – 5%			-	100%	95%	5%
HDPE	-	100%			-	-	-	-
Steel	100%	-			-	100%	-	100%
Fiber Reinforced Plastic	-	-			-	-	-	100%
PCCP	100%	-			-	100%	-	100%
Concrete Pipe	-	-			-	100%	-	100%

3.5 Municipality Water Services

The amount of water usage per person per day varies greatly from one family to another. Similarly, the average water supply per capita per day can also be different from city to city. The average daily supply of water per person reported by Utah State University in 2018 was 137 Gallons (Folkman, 2018), which is approximately 520 litres. The differences were significant comparing between the reported values to the surveyed daily water supply value per person from the four Canadian cities in this survey. In Table 8, the estimated water supply amount is recorded although, where the it was not responded by City C participant, however, the average amount of water supplied can be found on individual municipality websites (City C, 2019). City A reported to supply 474 mega litres of water per day in their system, considering the approximate population in the city, the average amount of water supplied per person per day is estimated to be 316 L/capita/day. From City C municipality website, the information related with water supply per day was 235 mega litres, which is estimated to be supplying 310 litres per capita per day. The reported average water supply from Utah State University was 520 L/capita/day (Folkman, 2018), which has comparable higher average value in this survey. Although, this supply rate may change when survey sample size increases.

Table 8. Surveyed Estimated Water Demand in Different City

City A	**City B**	**City C**	**City D**
474,000,000L/Day	180 L/Capita/Day	Not Responded	250 L/capita/Day

The amount of water supplied in each city does not indicate that all the water was successfully delivered to its users. Responses to a question about water loss are summarized in Table 9. According to these responses, the reported total water loss the water loss is approximately 10% with some degree of deviation. City D, however, indicated a 1% loss for each of all their systems, but they also question those values themselves. Based on reports by Utah State University Survey, on average, water loss due to leakage is roughly 10% of all the water supplied (Folkman, 2018). This is a very large amount of water lost for water systems, where the water lost due to system leakage was not even considered. This amount of water loss indicates a severe issue in the water systems, such that corresponding mitigation actions should be evaluated and executed to relieve the situation. Considering the water lost through both system leakage and breakage, the percent of unaccounted water may be even higher.

Table 9. Total Water Loss Percentage

Systems	City A	City B	City C	City D
Distribution (6" - 12")	0 - 10%	10% - 20%	10% - 20%	1%
Transmission (12" - 24")	0 - 10%	0 - 10%	10% - 20%	1%
Transmission (>24")	0 - 10%	0 - 10%	0 - 10%	1%

The selection field in the survey only had choices of percentages in ranges, which limited the answer choices for respondents. This can be improved in future surveys by providing more refined ranges in the selection field. Also, the percentage ranges are set up for total water loss, instead of water loss due to breakage or leakage, which can also be addressed in future surveys by asking more specific questions.

3.6 Municipal Water Main Break Rate

Understanding where a system has most issues is an important process, such that mitigation arrangements can be made accordingly to prevent similar problems in the future. Based on the recent paper by Grigg (Grigg, 2019), an approximate average failure factor of 0.25 breaks per mile per year was reported, which is approximately 0.155 breaks per kilometer per year. The average failure rating/factor was based on survey data collected from past 40 years (Grigg, 2019).

The estimated number of breaks that occurred in the water systems of the four surveyed cities over the past year are presented in Table 10. The letters D and T represents distribution and transmission systems, respectively. Cities A, C and D reported an approximate value of 300 breaks in the past year, while City B indicated an estimated 1200 breaks occurred in the past year. The estimated failure factor/rating reported in Table 10 ranges approximately from 0.06 to 0.15 breaks per kilometer per year for Cities A, C and D, which is relatively close to the average failure factor/rating of 0.155 breaks per kilometer per year. City B has an approximate 0.2 breaks per kilometer per year. The significant number of breaks in City B indicates serious issues in their water main system, such that a thorough assessment should be performed on the system to identify and mitigate these risks.

Table 10. Break percentage for Different Materials

Number of Breaks/Failure Factor (Rating)	City A			City B			City C			City D		
	300 Breaks			1200 Breaks			300 Breaks			386 Breaks		
	0.06 breaks/km/year			0.2 breaks/km/year			0.15 breaks/km/year			0.096 breaks/km/year		
% Breakage	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")
Cast Iron	45%	4%	-	70%	5%	-	40%	5%	5%	80%	8%	-
Ductile Iron	35%	4%	-	20%	5%	-	35%	5%	-	-	-	-
Asbestos Cement	4%	1%	-	-	-	-	-	-	-	10%	1%	-
PVC	4%	1%	-	5%	-	-	5%	-	-	-	1%	-
HDPE	~0%	1%		-	-	-	-	-	-	-	-	-
Steel	-	-	2%	-	-	-	-	-	-	-	-	-
Fiber Reinforced Plastic	-	-	-	-	-	-	-	-	-	-	-	-
PCCP	-	1%	4%	-	-	-	-	-	5%	-	-	-
Concrete Pipe	-	-	-	-	-	-	-	-	-	-	-	-

From the table above, Cast Iron pipes have the highest break rating and Ductile Iron pipes have the second highest break rating. Also, around 80% to 90% of the breaks occurred in distribution systems for all four cities. Cities B and D did not have any breaks in their transmission systems with pipe diameter over 24 inches. Based on these findings, municipalities are able to prepare for the immediate future, and make justified actions. These percentages represent the frequency of the break, however, the extent or the magnitude of the breaks were not reported. It is suggested to include in future survey questionnaire for data collections. All the breaks occurred in the past year in each city, the percentages in Table 10 indicates the estimated percent of breaks for different materials. The total percentages ideally should add up to 100% in each city, however, City A and B have some inconsistency in the total percentages that may be caused due to human errors.

The percentages are good representation of the condition of the overall systems. However, they do not fully represent the condition of individual materials. For instance, Ductile Iron has a 5% of overall breaks in City C's transmission system, but it does not indicate the material is in fair or good condition. A material may only have a very small portion within the overall water system, where the entire system may be having breaks occurring over and over. Therefore, in order to have a better interpretation of the condition of various pipe materials in different cities, a failure rating/factor analysis for each material in different systems was conducted and the results are reported in Table 11.

Table 11. Estimated Failure Factors for Different Materials in Different Systems

Failure Factor (breaks/km/year)	Distribution System (6" – 12")				Transmission System (12" – 24")				Transmission System (>24")			
	City A	City B	City C	City D	City A	City B	City C	City D	City A	City B	City C	City D
Cast Iron	0.23	0.26	0.18	0.56	1.50	0.44	0.33	2.78	-	0	0.43	-
Ductile Iron	0.11	0.48	0.23	-	0.30	1.33	15.00	-	-	0	0	-
Asbestos Cement	0.30	0	-	0.04	0.13	0	-	0.04	-	-	0	-
PVC	0.01	0.06	0.04	0	0.01	0	0	0.02	0	-	0	0
HDPE	0	0	-	-	0.19	-	-	0	0	-	-	0
Steel	0	-	-	-	0.00	-	0	0	0.08	-	0	0
Fiber Reinforced Plastic	-	-	-	-	-	-	-	0	-	-	-	0
PCCP	-	-	-	-	0.09	-	0	0	0.06	0	0.33	0
Concrete Pipe	-	0	-	-	-	0	-	-		0	-	-

The analyzed results are the most important findings from the surveyed data sets and were calculated using three steps from previous data collections. The steps are as following:

1. *Length of Different Systems (Figure 1) x Material Percentage of Water Mains (Table 5) = Length of respective material under different system*
2. *Break Percentage for Different Material (Table 10) x Total No. of Breaks Occurred in Past Year (Table 10) = No. of Breaks Each Material Type Occurred in Different Water Systems*
3. $\frac{No.\ of\ Breaks\ Each\ Material\ Type\ Occurred\ in\ Different\ Water\ Systems}{Length\ of\ Respective\ Material\ Under\ Different\ System} = Failure\ Factor$

First, by using the percentages of each material (Table 5) in different cities multiplying the corresponding water pipe lengths (Figure 1). The length of the pipe used for the calculation was the lower boundary of the data range in order to get a conservative value, since the lower the length of pipe, the higher the failure factor. In addition, the break percentage recorded in Table 10 was used to multiply the total breaks for each city to find the number of breaks for each material in different systems. Then, by dividing the breaks for each material by the corresponding number of pipe length in kilometer, the failure rating/factors were attained. These values were calculated based on assumptions and estimations, in which case, they were only calculated to provide a reference for water utility providers to consider. Nevertheless, assuming that the percentage values entered by participants are fairly accurate, then the values can be good indicators about what parts of the system and what material types should be of concern to municipalities.

From Table 11, a higher failure rating or factor indicates a material in poorer conditions l, where 0 indicates a pipe material that is in good conditions with no break occurred. The highest failure rating/factors were Ductile Iron in City C's transmission system with a diameter range from 12" to 24", with a value of 15.0 breaks per kilometer per year. This high failure indicator confirms that the percent breakage of material shown in Table 10 does not represent the full picture of the material condition, however, with these failure rating/factors, the conditions can be clearly interpreted. In general, higher failure rating/factors were observed for Cast Iron and Ductile Iron pipes within the water system, meanwhile, transmission system with diameter between 12" to 24" are having a poorer performance compared to other diameter pipes. Evidently, water utility providers should focus on a mitigation strategy for their Ductile Iron and Cast-Iron pipes in their water systems, especially for transmission system with diameter of 12” to 24” to prevent any potential risks in pipe breakage.

3.7 Chapter Conclusion

Through this survey on the four Canadian municipalities, the information regarding water systems were summarized for a conclusion on the differences as well as similarities between the cities. Furthermore, the proportions of the materials consisted of each city's water system are listed for reference. The installed water pipe material is relatively different from city to city. In addition, information collected on service connection pipe material as well as method used for service connection installation has been limited in the past. Therefore, in this pilot survey the water system service connections were being discussed, where the information collected can be useful for future pipe renewal, such that corresponding project planning can be made ahead of the construction for the types of water main materials the service connection pipes located.

Water loss and pipe breakage have been the most important issue encountered by water utility providers. With this survey, water system conditions of the four surveyed Canadian cities were determined along with their materials within the systems, all these conditions were reported as perceived. The factors/rating for each city as well as for different materials were analyzed to provide references to the water industries for consideration. It was clearly shown that pipe material made of Ductile Iron and Cast Iron are having major issues in all four surveyed cities, especially in the transmission systems with diameter between 6" to 12". Therefore, it is suggested that water utility providers to arrange an immediate renewal programs for the high failure water mains materials, in order to mitigate these apparent risks and prevent any potential breaks.

Chapter 4: Municipal Water Main Condition Assessment and Repair Methods

4.1 Introduction

In order to provide safe potable water to citizens, the utility provider will not only have to consider the status, but also recognize the rehabilitation and replacement methods used for mitigating the issues discovered in the system. By comparing replacement and rehabilitation methods from city to city, as well as the factors affecting decision making on which methods are chosen for pipe renewal, the water main rehabilitation industry will be able to make corresponding plans and changes in their business strategies.

4.2 Condition Assessment for Water Mains

Condition assessment refers to all activities that are employed to assess whether the overall quality of an existing system, in this case water mains, are sufficient and suitable for delivering safe potable water to the customers. After implementing condition assessment, consequent replacement or rehabilitation methods should able to be determined based on the assessed results. Most utilities currently try to fix the broken pipe as they occur, while not plan ahead to mitigate the essential issues (Grigg, 2019). With the implementation of regular condition assessment of water mains, municipalities will be able to understand the existing circumstance of the water mains and mitigate as early as possible.

The technologies implemented for condition assessment by the surveyed cities are listed in Table 12 below. All of the surveyed cities have implemented methods of condition assessment and monitoring, however City B applied acoustic sensors as the only technology for assessment and monitoring. From the table, the most common technologies used are acoustic sensor, ultrasonic wall thickness testing, as well as smart pigging. Smart pigging is expensive to perform, so it is interesting that City A and C both applied this technology for condition assessment of their system.

Hydrostatic testing on the other hand was only implemented by City A, which is surprising as well, as possible pipe leakage can be detected by monitoring the pressure drop in the system using this test method.

Non-destructive testing (NDT) methods evaluates the pipe in detail for cracks or small fractures without damaging the pipe itself (Bontus, personal communication, 2018). However, this does not mean other methods will damage the pipe during assessment. Based on the survey, no non-destructive testing was implemented by any of the cities in the past, where limitation for NDT technology may be the reason why it was not used. As water has to be shut off to perform NDT tests, while constant water has to be delivered.

Table 12. Technologies for Condition Assessment and Monitoring

Technologies	City A	City B	City C	City D
Acoustic Sensors	✓	✓	✓	✓
Ultrasonic Wall Thickness Testing and Monitoring	✓	-	✓	✓
Smart Pigging	✓	-	✓	-
Hydro Static Testing	✓	-	-	-

Aside from assessment of water mains using advanced technologies, many other methods or observations were also used for condition assessment. Table 13 stated several methods by respondents. All four cities have used other methods for assessing their water systems, however, number of breaks is the most common methods that was used by all. Most cities that responded have implemented more than one of the quantitative and qualitative methods, while only City B used one of the listed methods. For City D, Hazen–Williams C-Factor modeling was used for their

PVC pipes. City A reported other methods that were not provided in the survey, such as soil resistivity testing around buried mains and number of non-insulated service connections. Which can be good factors to consider in future surveys.

Table 13. Other Methods for Condition Assessment

Methods	City A	City B	City C	City D
Number of Breaks	✓	✓	✓	✓
Water Quality (Odor, Color, etc)	✓	-	✓	✓
Age of Pipe	✓	-	✓	✓
Hazen-Williams C- Factor	✓	-	-	✓
Other	Soil Resistivity, Number of Non-insulated Service Connections	-	-	C – Factor modeling used for PVC

In future surveys, it may be useful to include information related to, how often, and why each of the implemented technologies and methods were used. As a result, condition assessment methods can be further elaborated and explained, also a more accurate evaluation on the results of the assessed system will be attained.

4.3 Water System Requiring Immediate Repair

From the survey response, the water systems that require immediate repair are reported, where the percentage of pipe systems requiring immediate repairs are shown in Table 14 below. The average percentage of the total system that requires immediate repair is around 5% to 10% in each city. This percentage range is comparable to the reported percentage in the Canadian Infrastructure Report Card, which indicated that 12% of water systems in poor or very poor condition will require immediate replacement or rehabilitation (CFM, 2016). City D reportedly has a 35% of the total systems length that was repaired annually, which represents the entire water system of that city.

Table 14. Percentage of System Require Immediate Repair

<table>
<tr><th>Systems</th><th>City A</th><th>City B</th><th>City C</th><th>City D</th></tr>
<tr><td>Distribution (6" - 12")</td><td>5%</td><td>5%</td><td>10%</td><td rowspan="3">35%</td></tr>
<tr><td>Transmission (12" - 24“)</td><td>5%</td><td>5%</td><td>5%</td></tr>
<tr><td>Transmission (>24“)</td><td>5%</td><td>0</td><td>5%</td></tr>
</table>

4.4 Decision Making Criteria

The decision-making criteria refers to a set of basic requirements, such that when the requirements are met, consequent decisions will then be made. In municipal water mains, the decision-making criteria can be certain numbers of breaks over a set length of pipe, or in a set period of time, or all together. Table 15 recorded the decision-making criteria for when rehabilitation or replacement method will be performed for different cities. City A stated that the number of breaks is not a driving factor in making decisions on whether to perform renewal actions. City C reported a criterion of 300 breaks per year in order for them to start repairing the water systems. City D reported a more comprehensive decision-making factor, where if 11 breaks occurred from valve to valve or 6 breaks happened in 5 years from valve to valve, then repair will be required. It is suggested in future surveys, a more specific question should be included, such as specifying the number of breaks occurred in the past year over a unit length of the pipe. Also, a new guideline is recommended to be developed in the future, in order to provide a guide for municipalities in Canada to consider when making pipe renewal decisions

Table 15. Criteria (Number of Breaks) Leading to Perform Pipe Renewal

City A	City B	City C	City D
Number of breaks is not a driving factor in making decision	No Response	300 breaks/ year	11 breaks from valve to valve or 6 breaks in 5 years valve to valve

4.5 Comparison between Replacement and Rehabilitation Methods

CIPP and Spray-on rehabilitation methods has become more popular in the water industry for water main repairs. Before rehabilitation was developed, replacement methods were the main go-to approaches. Even now, open cut remains the primary method used (Folkman, 2018). In the following sections, a comparison was performed between different types of repair or replacement methods were performed based on surveyed data in Table 16, 17, 18, and 19. The lengths of pipe repaired or replaced in different cities using different methods are presented. Also, the unit cost and annual budget for each method are summarized and described.

4.5.1 Lengths of Pipe Fixed During Respective Duration

The length of water mains fixed in the past years using either rehabilitation or replacement methods were reported by the surveyed city representatives and are recorded in Table 16 below. The replaced or repaired pipe lengths during past year, two years and five years are listed for discussion. Generally, most of the repair or replacement method used are for the distribution systems in each city. This observation corresponds to the s findings from previous survey (Folkman, 2018), where more breaks occurred in the distribution system. Based on the data reported, cities implement replacement and rehabilitation methods fairly equally in areas where the population density is higher. Cities B and C reported using rehabilitation and replacement methods on approximately the same length of pipe, while Cities A and D are more reliant on pipe replacement methods. This may be due to the large land areas, where population are more spread out. Based on the reported lengths repaired or rehabilitated in each city, it is observed that City A had least repairs performed for their water mains, while City B had significant more repairs. In the previous section, City B was reported to have 1200 breaks over the past year, this explains the reason why more pipe lengths were repaired. Yet, Cities A and C both reported 300 breaks over the past year, while City A repaired less of the system compared to City C.

Table 16. Estimated Lengths of Pipe Repaired During Respective Durations with Different Methods

Methods	System/ Past Years	City A (km)			City B (km)			City C (km)			City D (km)		
		1	2	5	1	2	5	1	2	5	1	2	5
Rehabilitation	Distribution (6" - 12")	-	2	2	30	60	200	4	10	30	1.3	2.1	3.7
	Transmission (12" - 24“)	-	-	-	4	8	20	-	-	2	-	0.3	0.7
	Transmission (>24“)	-	-	2	-	-	-	2	-	-	-	-	-
Replacement	Distribution (6" - 12")	6	10	20	40	80	200	6	10	30	14	28	72
	Transmission (12" - 24“)	2	2	6	6	10	15	2	-	-	0.9	1.8	5.1
	Transmission (>24“)	-	-	2	-	2	-	-	-	4	-	-	-

4.5.2 Methods Implementation Comparisons

Based on the information collected on the length of water mains replaced or repaired in the past years, the percentage of each methods used were also surveyed through the online questionnaire. The percentages for corresponding rehabilitation or replacement methods are listed in Table 17 below. Similar results were shown comparing to the results obtained from Table 16. Both Cities A and D implemented replacement methods much more than rehabilitation, while Cities B and C implemented the two methods relatively equal. For the replacement methods implemented, open cut was still the primary method. Although pipe bursting and HDD were used in Cities A and D, but the extent was very small compared to open cut. CIPP was the main technique used for rehabilitation method. In Cities B and C especially, where spray-on and slip lining were not used. City D used all types of rehabilitation and replacement methods for their water systems; however, open cut was used significantly more in comparison. Another noticeable fact from Table 17 is that every city's water transmission system with diameter greater than 24 inches was replaced all with open-cut method. As a matter of fact, since water transmission systems are buried mostly in less populated areas, therefore open-cut replacement is deemed to be the most efficient method for fixing the issues.

Table 17. Estimated Percentage of Methods Used for System Restoration

Methods	City A			City B			City C			City D		
	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")
Open Cut	90%	95%	100%	50%	50%	100%	55%	95%		83%	87%	100%
Pipe Bursting	5%	5%	-	-	-	-	-	-	-	3%	-	-
HDD	5%	-	-	-	-	-	-	-	-	4%	3%	-
Spray-on	-	-		-	-	-	-	-	-	2%	-	-
Slip Lining	-	-	-	-	-	-	-	-	-	4%	6%	-
CIPP	-	-	-	50%	50%	-	45%	5%	--	4%	4%	-

Comparing between Table 16 and 17, discrepancies in the collected information were observed. The two tables should be able to support one another, where the general information should be able to match. For instance, if a certain length repaired using rehabilitation method was reported in Table 16, then Table 17 should also have a percentage value for any one of the rehabilitation methods listed. Cities A, C and D all had discrepancies in their survey responses. City A reported to have rehabilitated 4km of their transmission and distribution system, however, in Table 17 no percentage was indicated for any of the rehabilitation methods. For City C, 6km of transmission systems was both replaced and rehabilitated, but was not indicated in Table 17. Finally, City D reported to have no transmission system being either replaced or rehabilitated in Table 16, yet 100% of transmission systems was replaced using open-cut method. These discrepancies may be due to human errors during survey, nevertheless, in future surveys, clarification on data discrepancy should be requested from participants to ensure the accuracy of the data set.

4.5.3 Water Main Rehabilitation and Replacement Unit Costs

Unit cost is one of the main factors affecting the decision making on types of methods to be used for water main renewal. The unit cost related with different methods in different cities are listed in Table 18 from survey responses. In the survey, the drop-down list had limited choice selection field, where "over $1500/m" was not defined more specifically. Initially, it was expected that $1500/m was the high end of the unit cost. In turn, the unit cost was realized to go much higher. This issue should be addressed in future surveys with more and higher choice selection in unit costs.

Table 18. Estimated Unit Cost for Different Methods

Methods	City A ($/m)			City B ($/m)			City C ($/m)			City D ($/m)		
	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")	D (6" – 12")	T (12" – 24")	T (>24")
Open Cut	Over 1500	1500	Over 1500	Over 1500	Over 1500	Over 1500	1100	1400	Over 1500	1850	2200	2900
Pipe Bursting	1400	1400	-	-	-	-	-	-	-	1900	-	-
HDD	-	-	-	1200	-	-	-	-	-	2200	2500	-
Spray-on	-	-	-	-	-	-	-	-	-	1100	-	-
Slip Lining	-	-	-	-	-	-	-	-	-	1000	1900	-
CIPP	1500	-	-	1000	Over 1500	Over 1500	800	1000	Over 1500	1200	1300	-

In general, unit cost for rehabilitation methods are lower in comparison with pipe bursting, HDD and open cut for the same diameter of pipe. However, it was observed that the unit cost also increases with the increase of pipe diameter. The unit cost of rehabilitating or replacing a meter of pipe does not represent the entire cost of a project, as other costs during construction may significantly increase the total project. As a result, it is important for the utility providers to make correct decision on which methods to choose from, in order to minimize issues that may occur during construction for a certain method.

4.5.4 Analysis of Pipe Renewal Construction Cost

From both Tables 16 and 18, the estimated renewal construction cost can be determined for the past year. By calculating the annual cost for rehabilitation and replacement, the cost difference can be clearly shown and compared with annual budget in the next section. Since the unit cost were mostly reported as over $1500/m for in many cases, therefore, the average unit cost for rehabilitation and replacement will be using city D's data set, which provided a much more comprehensive data value that go above $1500/m. The average unit cost for replacement method for water distribution system renewal is approximately $2000/m, and average unit cost for rehabilitation method for the same system is $1100/m. For transmission system with pipe diameter between 12" to 24", the average unit cost is $2350/m for replacement and $1600/m for rehabilitation. In case where pipe diameter is 24" and above, the unit cost is expected to be much similar, as a result, most often utility providers will use the conventional open-cut replacement method, with $2900/m of unit cost. One of the main reasons for using open-cut is because most 24" and larger pipes are buried in open areas instead of the condensed area, such that open-cut is the easiest and most used method for these cases.

Table 19. Past Year Estimated Pipe Renewal Cost

Systems	City A ($ in Million)		City B ($ in Million)		City C ($ in Million)		City D ($ in Million)	
	Rehab	Replace	Rehab	Replace	Rehab	Replace	Rehab	Replace
Distribution (6" - 12")	0	12	33	80	4.4	12	1.43	28
Transmission (12" - 24")	0	4.7	6.4	14.1	0	4.7	0	2.12
Transmission (>24")	0	0	0	0	3.2	0	0	0
Total Cost	0	16.7	39.4	94.1	7.6	16.7	1.43	30.12

According to the above table, the cost spent on renewal using replacement method is significantly higher than the cost spent on rehabilitation methods. For instance, according to the pipe renewed in City B and C for distribution system, the length repaired is approximately 50% to 50%, yet the cost spent on replacement is more than double the cost for rehabilitation. Evidently, rehabilitation method is a much more efficient pipe renewal type that could save tens of millions of dollar.

4.5.5 Estimated Annual Budget for Water Main Renewal

The estimated annual budget from municipal representatives are reported in Table 20. The municipalities apply different number of budgets for their utilities, and for water mains, it most likely be dependent on the frequency and magnitude of pipe breakages. Based on the data in Table 20, the annual budget planned for replacement are generally higher than for rehabilitation for all cities. In Cities B and D, the differences are approximately $50 Million in budget, which the budget difference is a significant difference. From Table 17, City B indicated that to the repair work was split evenly for both rehabilitation and replacement methods, however, Table 20 suggests that the annual budget for City B using replacement is double the budget for rehabilitation. In general, the budget for distribution system are higher comparing to the budget for transmission systems, this is expected as a large portion of the water mains are distribution system, and most of the breaks occurs in distribution system. Out of all four cities, City B has the highest budget planned, indicating more repair work will be required for their water systems than other cities.

Table 20. Estimated Annual Budget for Water Main Renewal

Systems	**City A ($ in Million)**		**City B ($ in Million)**		**City C ($ in Million)**		**City D ($ in Million)**	
	Rehab	**Replace**	**Rehab**	**Replace**	**Rehab**	**Replace**	**Rehab**	**Replace**
Distribution (6" - 12")	2	8	50	100	5.5	7.5	1	56
Transmission (12" - 24")	1.5	2	10	5	-	3	0.5	3
Transmission (>24")	0.5	2	-	-	5	5	-	-
Total Budget	4	14	60	105	10.5	15.5	1.5	59

Comparing Table 20 to Table 19 in terms of money spent in both renewal methods, the discrepancy has decreased for Cities B and C, where the past annual spending on replacement method was more than double the amount for rehabilitation method. Yet, the planned total budget for Cities B and C will be decreased from almost 3 times more than the cost for rehabilitation to approximately 1.8 times more. This indicate a significant change in future decision on which method to implement for water systems renewal. Where, for transmission pipes with diameter between 12” to 24”, the planned budget for rehabilitation is even higher than the replacement methods. On the other hand, the annual budget reported for Cities A and D does not show a tendency for using rehabilitation method in place for replacement method. Once again, the decision may be influenced by other factors instead of only by construction cost.

4.6 Renewal Method Decision Making Factors

To fully understand the decision making on whether replacement or rehabilitation method should be used for renewal is an important and hard choice to make. Many factors will affect the final decision making. Based on discussion with experienced industrial personnel (Bontus, Personal Communication, 2019), 10 major factors were listed in the survey for municipality participant to rank the importance of each in their opinion. It was anticipated that the rank for factors may explain why for City A and D would stay in use of replacement method instead of innovative rehabilitation method.

Table 21. Ranking of Factors' Importance in Making Decisions on Water Main Renewal Methods

	City A	City B	City C	City D	Average
Product Life	2	1	1	4	2
Project Cost	7	4	4	8	5.75
Standard Design and Construction Guideline	6	5	8	2	5.25
Environmental Impact	1	2	3	5	2.75
Locations (Rural vs Urban, Ground Conditions)	8	6	7	7	7
Minimal Disruption/ Down Time	10	3	5	10	7
On Site Duration	9	7	6	6	7
Possible onsite Uncertainties	3	8	2	9	5.5
Contractor Technical Comfort Level	5	2	10	1	4.5
Availability of Contractor	4	10	9	3	6.5

The 10 factors are listed in Table 21 above, where the numbers from 1 to 10 ranking for each city represents the importance of each factor towards the decision making of choosing for renewal methods. In the ranking, 1 indicates highest importance, and 10 indicates the least important factor, also, factors with same importance can be ranked at the same level. In general, the factor's importance is very different in each city, for instance, City D reported to consider contractor technical comfort level as the most important factor, but City C perceives it as the least important factor. By comparing the average rating of the factors, product life is one of the most important factors considering it has an average rank of 2. Environmental impact and contractor technical comfort level is also important for most of the cities, except City C. Looking at the ranking, both Cities A and D put project cost in lower position compared to Cities B and C. Evidently, This ranking explains and supports the finding in previous sections, where even though the unit cost and project cost for using rehabilitation can save millions of dollar compared to replacement methods, Cities A and D would still prefer using mostly replacement in future water main renewal projects. Other factors involved in a project are deemed more important by these cities, especially product life. All of the listed factors should be considered in the planning phase of a rehabilitation or replacement project, however, depending on water utility's perceptions and previous project experiences, some factors was not encountered in the past to be considered as an issue, such that the factor was ranked lower in importance.

4.7 Chapter Conclusion

The responses collected from pilot survey questionnaire indicates that all the responded cities implement ways of technologies and methods in determining the condition of their water mains. The decision-making criteria on when to perform pipe renewal program is lacking a consistent guideline throughout Canada. With the data collected from the survey regarding the methods of water pipe renewal, comparisons made on past pipes renewed, percent of methods implemented, unit costs, as well annual budget, a good understanding of current water industry was achieved. Currently, replacement methods using open-cut is still the primary technique for pipe renewal, however, two out of four cities considered using CIPP trenchless technology and open-cut to a same degree. Simply from the survey results, clearly more replacement method was used than rehabilitation. However, it is a much cheaper method to implement rehabilitation, the unit price is much lower, which consequently, could save up almost half the construction cost compared to using replacement. Nevertheless, Cities B and C have planned budget with a tendency to use more rehabilitation method compared to the past years. While in contract, Cities A and D did not plan for change in methods as project cost is not one of the priorities affecting their decision in choosing the method for pipe renewal. Supposedly, with more improvement on trenchless rehabilitation technologies, cities will start gaining more confidence in implementing rehabilitation methods for future projects.

Chapter 5: Water Main Rehabilitation Using CIPP and Spray-On Methods

5.1 Introduction

According to previous findings from survey results, it was clearly shown that replacement methods are still being implemented as the main renewal methods for water main systems. Even though rehabilitation methods has a cheaper unit cost and can save up to half the amount compared to replacement. Also, from the planned annual budget, the trend still shows that cities with broader areas will not consider using rehabilitation as the main method. One of the key finding from the survey was that product life is the focus for utility providers while making decision on which method to choose from instead of cost. Based on comments from the survey results conducted by Utah State University, the use of CIPP, HDPE and spray-on, are high cost methods that are only used when open-cut methods are not feasible, and were only used for large diameter pipes, where many of the utilities are not happy with the results (Folkman, 2018). However, significant improvements have been achieved throughout years of development of CIPP products and installation methods, which have contributed to enhancing underground sewage and water systems while saving millions to billions of dollars for government and industry. In this chapter, the product performance are researched and described to provide support for the findings from the survey to prove that the CIPP and Spray-on technologies are alternative pipe renewal methods in the near future.

5.2 Development of water main rehabilitation methods

Before CIPP was introduced in the 1970s, the deterioration prevention method for pipe internal surface was spray-on lining with cement mortar (AWWA, 2014). The method was first implemented in 1933 in New Jersey for water systems (Ellison et al., 2010), and was only applied to larger sized pipes, since the spraying device had to be dragged manually by workers. In the

1950s, remote sprayers were invented, enabling smaller sized pipes to be rehabilitated using cement mortar lining (Ellison et al., 2010). Cement mortar deteriorates more easily, affecting the water quality by increasing the pH after a period of time (Ellison et al., 2010); therefore, polymer products were slowly developed for use in water mains. Epoxy came into the market in early 1980s and its use spread across Europe and Japan (Ellison et al., 2010). Late in the 1980s, the method was gradually accepted by United States markets, and standards were developed for its use. Approval by the American Water Works Association (AWWA) for the spray-on method was finally gained in the United States in 2008 (Ellison et al., 2010). Recent developments in polymer lining for water mains involves the use of epoxy, polyurethane and polyurea, which can provide even faster cure time than cement mortar and epoxy (Dudley, 2000).

The rehabilitation of underground utilities using CIPP started in 1971 by Insituform founder, Eric Wood (Lee and Ferry, 2007). The idea to rehabilitate pipes without open trenching began while Wood was working on a leaking pipe in the United Kingdom, where the pipe was difficult to replace due to its location. After the successful implementation of this innovative process, it was commercialized and patented as cured-in-place pipe (CIPP) in 1977. This became the main area of expertise for the company Insituform Technologies, which operated mainly in the United Kingdom (Kozman, 2013). In 1994, Wood's United States patent expired, allowing CIPP to be employed by other pipe rehabilitation companies around the globe. According to Kozman, CIPP technology was not widely adopted in North America until the early 2000s (Kozman, 2013). However, the use of CIPP was reported in Winnipeg, Canada, as well as in the United States in the 1970s (Bontus, personal communication, 2018). Due to the design flexibility, installation efficiency, as well as its wide range of applications, CIPP became one of the most ideal method for gravity pipe rehabilitation. During the first years of development, the method was implemented on projects with pipe sizes ranging from 2 inches to 120 inches in diameter and was able to accommodate different shape of pipes, direction changes, as well as pipe size change (Kozman, 2013). Kozman mentioned that it was not until the early 2000s when water mains started to use CIPP method for rehabilitation in North America (Kozman, 2013). However, it was known that Insituform applied this technique in North America in the mid-1990s. The progressive development of spray-on and CIPP rehabilitation methods is summarized in Figure 3, where key advancements and the related year of occurrence are illustrated.

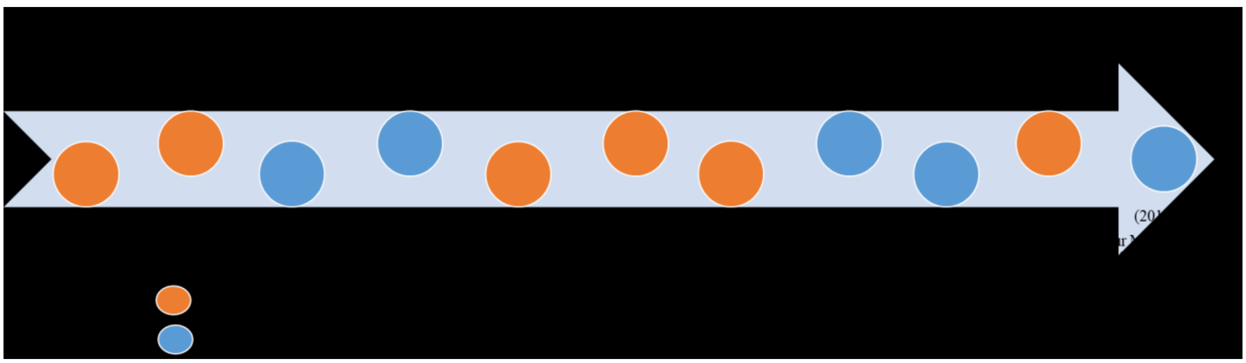

Figure 3. Pipe Rehabilitation Advancements Timeline

5.2.1 Water Main Markets and Products

In the present CIPP rehabilitation industry, most of the projects around the world that are related to water main pipes renewal project, the liner product usually belongs to one of the four major companies listed in Table 22. These companies typically provide lining services in regions where their corporate offices are located; in other regions, they allow local contractors or licensees to perform installations using their product and technology.

Table 22. CIPP Liner Product Information Summary and Comparison[1]

Company	Product Name	Diameter Range		Installation Length	Internal Pressure Capability	Installation Method	Certification	Composite Material	Internal Surface Material	Structural Ability
		inch	mm	m	psi					
Sanexen Water Inc.	Aqua Pipe	6 to 24	150 to 600	300	150+	Pull-in	NSF/ANSI Standard 61	Woven Polyester and Polymeric Membrane	Polyurethane Membrane	Class IV
Insituform/Aegion	Insitumain	4 to 96	100 to 2400	400	150+	Inverse	NSF/ANSI Standard 61	Resin Saturated Polyester (PE100) and Fiberglass	Polypropylene Coating	Class IV
Sekisui	Nordipipe	6 to 48	150 to 1200	300	200+	Inverse	NSF/ANSI Standard 61	Resin saturated Polyester and Fiberglass	PE coating	Class IV
HammerHead and RS Technik (Pipe Aquatec)	BlueLine	6 to 48	150 to 1200	N/A	up to 230 psi <12" up to 145 psi >12"	Inverse and Pull-in	NSF/ANSI Standard 61	Resin Saturated Polyester and Fiberglass	N/A	Class IV

The marketing location of the four corporations is shown on the map in Figure 4. It is noticeable that the most developed countries or regions have the highest competing market. This is due to the fact that countries such as United Kingdom, United States, Canada, Australia, Japan, etc., where the infrastructure was built in the late 1800s and early 1900s, have aged pipes that currently require rehabilitation or replacement. Therefore, more opportunities and bigger markets are present in these regions.

[1] *Information retrieved from: 1. www.Sanexen.com, 2. www.sekisuispr.com, 3. www.aegion.com and 4. www.pipe-aqua-tec.de)*

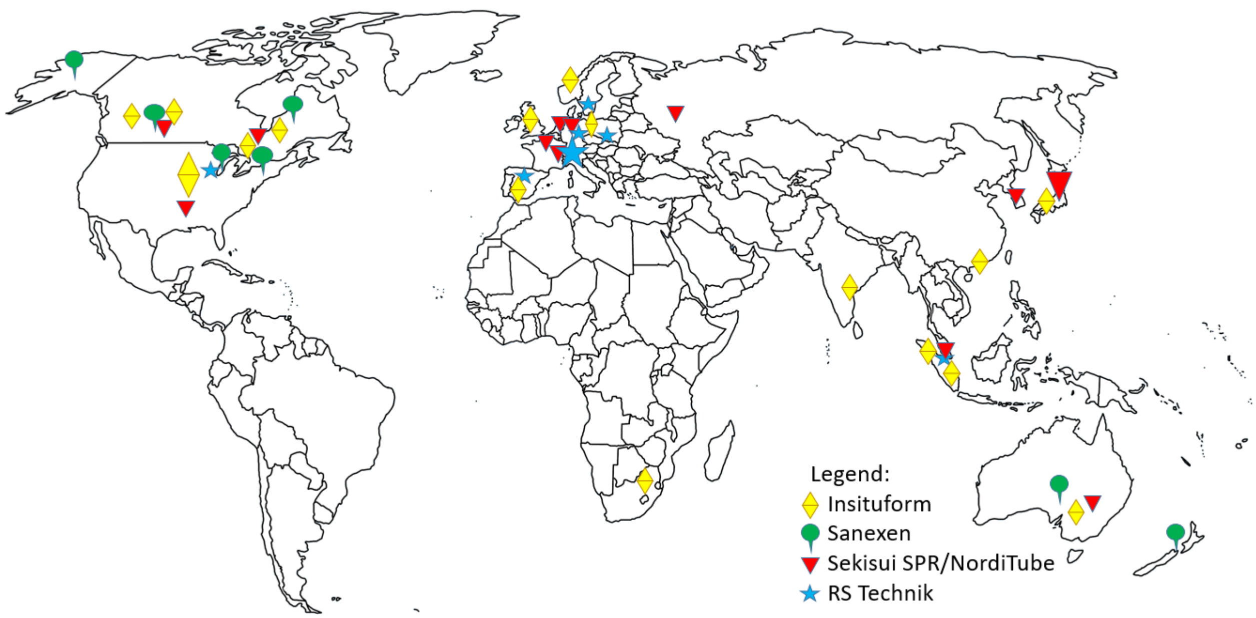

Figure 4. Current CIPP Water Main Liner Products Geo-Marketing

According to Table 22, each company designed their liner products differently, including the composite material used, installation method, and internal pressure capability. In general, most of these companies can manufacture and install their products in pipe sizes larger than 6 inches in diameter; however, Insituform can line pipes as small as 4 inches. For large diameter pipes, Insituform has lined water main pipes as large as 96 inches, while the use of the Sanexen product has been recorded for pipes up to 24 inches in diameter. In terms of internal pressure capability, all companies have ensured their product can withstand pressures reaching above 150 psi. Polyester and fiberglass are the main materials of the water main CIPP products, whereas polymer epoxy resin is the most commonly used chemical to provide the bond and tensile strength between the CIPP and host pipe. For these products to be safely used in potable water distribution systems, the liner product must be certified by the international water standard NSF/ANSI Standard 61.

5.3 Structural Classification of Liners

Prior to selecting the appropriate rehabilitation product and method for a pipeline, the degree of deterioration and structural condition of the host pipe needs to be determined. For gravity pipes, the liner design conditions depend on the deterioration status. In ASTM F1216, the design considerations for CIPP liners are presented for both fully deteriorated and partially deteriorated host pipes (ASTM, 2016). Failure is imminent with cracks and holes for fully deteriorated pipe, while a partially deteriorated condition is when joint leaks, root infiltration and exfiltration occur. The product selection for the repair of water mains and pressurized pipes depend on the structural condition of the host pipe. Liner products are classified into four classes as suggested by the AWWA M28 manual, with Class I for non-structural repairs, Classes II and III for semi-structural repairs, and Class IV for full structural repairs (AWWA, 2014).

Non-structural repair is applicable when the host pipe is structurally sound but requires internal joint seals and cathodic protection. The ideal method for this type of pipe renovation is spray-on lining. Semi-structural repair involves interactive liners such as CIPP; however, it does not require the liner to have the ability to survive burst failure of the host pipe nor long term pressure application. The difference between Class II and Class III liners is that Class II relies on adhesion to the host pipe, while Class III relies on the inherent ring stiffness of the liner (AWWA, 2014). Finally, fully structural repair requires independent liners (Class IV). This last class is considered when the host pipe has entirely failed and the CIPP liner is required to have the ability to support both internal and external loads. The minimum requirement for Class III and Class IV in terms of inherent ring stiffness is related to the self-supporting ability of the liner when the pipe is depressurized. Table 23 provides a comparison of the characteristics of each structural class. The AWWA M28 Manual does not provide quantitative guideline or standards of design. The current industrial design of pressure liners and coatings relies on ASTM F1216, but the criteria are often misinterpreted or improperly used (Bontus, 2017). Industry claims that spray-on products can provide semi-structural and even fully structural rehabilitations; however, in reality, this is challenging, as a very thick layer of the material would need to be used in order to provide the required strength. Therefore, CIPP is more suited in situations requiring structural support, as well as requiring less project cost relative to polymer spray-on products.

Table 23. AWWA M28 Suggested Structural Classification of Liners (AWWA, 2014)

Liner Characteristics	Class I	Class II	Class III	Class IV
	Non-Structural	Semi-Structural		Fully Structural
Internal Corrosion Barrier	Yes	Yes	Yes	Yes
Bridges Holes/Gaps at Pipe Operating Pressure	No	Yes	Yes	Yes
Inherent Ring Stiffness	No (rely on adhesion	No (rely on adhesion)	Yes	Yes
Long-term Independent Pressure Rating to be greater than pipe operating pressure	No	No	No	Yes
Survives Burst Failure of Host Pipe	No	No	No	Yes

5.4 Liner Design and Installation Criteria

Since the initiation of rehabilitation methods for underground pipes, engineering design methodology has been developing to enhance the service life of water mains more efficiently, as well as to ensure the design meets the baseline requirements. The related ASTM standards provides guidelines for the design and installation of liner products. If a liner product is applied to drinking water pipes, local water associations would also be involved to certify that the design is applicable for pressurized potable water pipes. In North America, the AWWA Manual M28 is always considered, along with ASTM Standards for any water main rehabilitation projects (AWWA, 2014). The M28 manual does not provide a quantitative design process but illustrates the essential steps to a water main rehabilitation project.

Both international associations, AWWA and ASTM, contribute to ensuring the design and construction are satisfactory for providing service to the public. In contrast, AWWA standards are applicable only to potable water delivery systems, where the AWWA manual M28 provides detailed procedures and equipment applicable to each stage of the installation processes. ASTM, however, provides detailed design, installation, and quality assurance procedures for different types of underground water utilities, as well as different types of rehabilitation methods. The standards associated with pipe rehabilitation design and installation are presented in Table 24: they were established for CIPP rehabilitation of sewer pipes using either inversion or pull-in installation methods, as well as standards for spray-on liner for potable water pipes (ASTM, 2009). Nevertheless, to date no existing standard has been specifically developed for the design and installation of CIPP for water main pipe rehabilitation. The current design of CIPP water main products from the four companies mentioned previously solely relies on equations in ASTM F1216 (ASTM, 2009), where the design of the minimum CIPP liner thickness for low pressurized pipe was specified. This design consideration, however, does not sufficiently describe the detailed behaviour of water mains, such as water pressure surge cycle and maximum water pressure that are present in these systems. Without consideration of these particular pressure characteristics of the system, the degree damage resulting from an incident could be disastrous, as the liner may not be able to support the maximum pressure in a water surge or the higher sustained pressure in the systems compared to low pressurized system, and this lack of design may result in a severe pipe breakage.

Table 24. Existing Standards or Manual Related with Rehabilitation of Gravity or Water Mains

Method of Rehabilitation	Standards	Standard Title	Year of Latest Revision	Specified Design Application	Summary
CIPP	ASTM F1216	Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube	2016	Gravity Main	Design and installation procedures for CIPP products installed using inversion method Design consideration for CIPP are in Appendix X1
	ASTM F1743	Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe	2017	Gravity Main	Installation procedure for CIPP products installed using pulled-in place method
Spray-On	ASTM F3182	Application of Spray-Applied Polymeric Liners Inside Pipelines for Potable Water	2016	Water Main	Procedure, performance requirements, QA/QC for rehabilitation of potable water mains using Spray-on polymeric coating
CIPP/Spray-on	AWWA M28	AWWA Manual - Rehabilitation of Water Mains	2014	Water Main	Water main rehabilitation required procedures and evaluations
Point Repair CIPP	ASTM F2599	The Sectional Repair of Damaged Pipe by Means of an Inverted Cured-in-Place Liner	2016	Gravity Main	Installation Procedure, performance requirements, QA/QC for rehabilitation of pipes sections using CIPP
UV Cured CIPP	ASTM F2019	Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Glass Reinforced Plastic Cured-in-Place Thermosetting Resin Pipe	2011	Gravity Main	Installation procedure for pulled in place CIPP products cured with ultraviolet light

5.5 Water Main Rehabilitation Procedures

The installation process for CIPP and spray-on rehabilitation requires much less work and time compared to the conventional dig and replace method. For water main pipes, activities usually consist of the installation of a temporary service by-passing system, excavation of access pits, cleaning of the internal surface of the pipe, and inspection before and after the lining process, as well as the lining process itself. Additionally, restoration work has to be done before the project is completed. These activities are compared with the similar procedures for sewer pipe rehabilitation by CIPP, as shown in Table 25. Spray-on liners have relatively similar installation procedures as CIPP; the main differences are related to the material and product involved. The importance of each activity is described in detail in the following sections.

Table 25. Installation Procedures of Gravity Mains and Water Mains

Construction Stages	Activities	Gravity Pipes	Water Mains
Pre-Lining	Service By-Passing	Occasionally	√
	Access Pits Excavation	Occasionally	√
	Internal Cleaning	√	√
	Pre-Lining Inspection	√	√
	Service Connection Plugging	-	√
Lining	Lining Process	√	√
Post Lining	Post Lining Inspection	√	√
	Service Connection Reinstatement	√	√
	Site Restoration	Occasionally	√

5.5.1 Service By-Passing

As installation may take a few days to accomplish, the pipe requiring rehabilitation needs to be shut off during the installation purposes. Water main rehabilitation requires a service by-pass system to be set up before the actual installation starts in order to provide continuous water service to local residents. Also, the service by-pass has to meet NSF/ANSI Standard 61. The by-pass often uses high density polyethylene pipes (HDPE) that are fused together and connected to nearby fire hydrants for a water supply (Matthews et al., 2012). These HDPE pipes will then be treated with disinfectants to ensure the quality of the water supplied to consumers (AWWA C651, 2005).

5.5.2 Access Pits Excavation

Once the host pipe is shut off and service by-passes are set up, excavation of access pits can start. These pits are constructed at the designated locations using a backhoe or vacuum track for soil removal. The access pits are often excavated at the turning point of the buried pipes, and the dimension of the pits will depend on the particular situation. Waste soil is either stored on site or removed from the site using a dump truck for recycling. Once the pits are fully excavated, a section of old pipe will be cut off for installation access for CIPP liner and cleaning.

5.5.3 Cleaning

In order for a CIPP liner to be effectively installed, internal surface of the host pipe needs to be cleaned. Table 26 shows the methods that has been used for cleaning, including the pros and cons of each operation. Previously, the most commonly used methods involved the use of hydraulic jet cleaning, mechanical drag cleaning, chain flail, and swabbing. Initially, a high-pressure water jet is sent through the pipe to remove debris and deposits, then a chain of scraper blades is dragged from one end to another to remove leftover material from the pipe. The pipe will then be swabbed with foam pigs or polyurethane foam by dragging using trucks, pushed by air or water pressure, or rack-feed boring to remove iron tuberculation. The newly developed technology for cleaning pipes is the Envirologics System, Tomahawk (Mudzingwa et.al. 2012), which draws a variety of grades and types of abrasives or stones using low pressure vacuum. It will remove tuberculation and debris in almost half the time compared of other methods (Cooper and Knight, 2013). More importantly, because of less impact stresses, this method will minimize the chance of damaging the wall of the host pipe and the service connections. When Tomahawk is used, no drying will be required after the operation, as water is not used during the cleaning process.

Table 26. Cleaning Methods Advantages and Disadvantages

Cleaning Methods	Advantage	Disadvantage
Flushing	Remove Impurities	Does not remove tuberculation
Air Scouring	Remove film and light weight debris	Does not remove tuberculation
		Service connection has to be isolated
Drag Cleaning with Chain Scraper	Removes internal encrustation and hard deposits	Potential damage to service connections
High Pressure Flushing		
Foam pigs and Swabs	Removes internal encrustation and hard deposits	Pig receiver station has to be set up
Power Boring	Removes internal tuberculation and corrosion	May damage service connections
Tomahawk Cleaning	remove debris with less time	High Cost
	without using water	
	better cleaned surface	
	exposes hidden leaking cracks at service connection	
	minimize potential damage to pipe wall and service connection	
	capable of using airborne camera to monitor the process	

5.5.4 Pre-lining Inspection and Service Plugging

Once the internal surface of the host pipe is cleaned, a pre-lining inspection will be conducted to check and record on the internal surface condition and visible defects that may affect the lining installation and performance. Furthermore, plugging of service connections will be completed at this stage for CIPP methods. Spray-on lining does not require capping, since the liner at the connection can be easily blown off after application. Capping of service connections prevents the flow of resin into the service pipe, which could block the non-rehabilitated pipe after curing. By using a robotic device equipped with CCTV, the visualization of the surface and location of service connections will be recorded, and the service connection will have to be reinstated after lining. Plugs are made of polyester materials such as PE and HDPE that are installed with an air-actuated piston and cartridge device on the remote robotic roller (Matthews et al., 2012). Pre-lining inspection helps to indicate leaking, remaining tuberculation, as well as issues that may affect the lining process. As such, this step is essential, and care must be taken.

5.5.5 Lining Process

The lining process is the key stage of the construction procedure, as all other activities are to ensure this step is successfully accomplished. Both spray-on lining and CIPP have similar preparation procedures, yet the actual lining for spray-on is much easier to implement. As for spray-on method does not require the process of inserting the liner, nor does it have to be concerned about plugging service connections.

5.5.6 Spray-on Lining Procedure

Before spray-on application, the polymer and resin should be warmed and sheared. Then, through access pits, the spray-on device with mixed polymer resin inside is sent into the cleaned pipe for coating as shown in Figure 5. The moving speed of the lining robotic device as well as its rotational speed will depend on the size of pipe, also will be decided by operator onsite based on actual situation. Several layers of spraying will be required until the desired thickness of resin is achieved. The minimum thickness is 0.04 inches (ASTM F3182, 2016). To cure the resin, a minimum temperature of 3°C should be obtained unless pre-approved by the manufacturer (ASTM F3182, 2016). The polymeric material used for spray-on lining is polyurea, polyurethanes and epoxies (AWWA C620, 2019), which provides durable coating to the internal surface of the pipe that increases flow rate and water quality, while enhancing the pipe condition (Rajasarkka et al., 2016). This method is applicable for almost all types of host pipe material. The limitations of this technique, however, are that lining cannot guarantee consistent thickness throughout the entire pipe, nor can the adhesion be ensured without testing (Bontus, 2018).

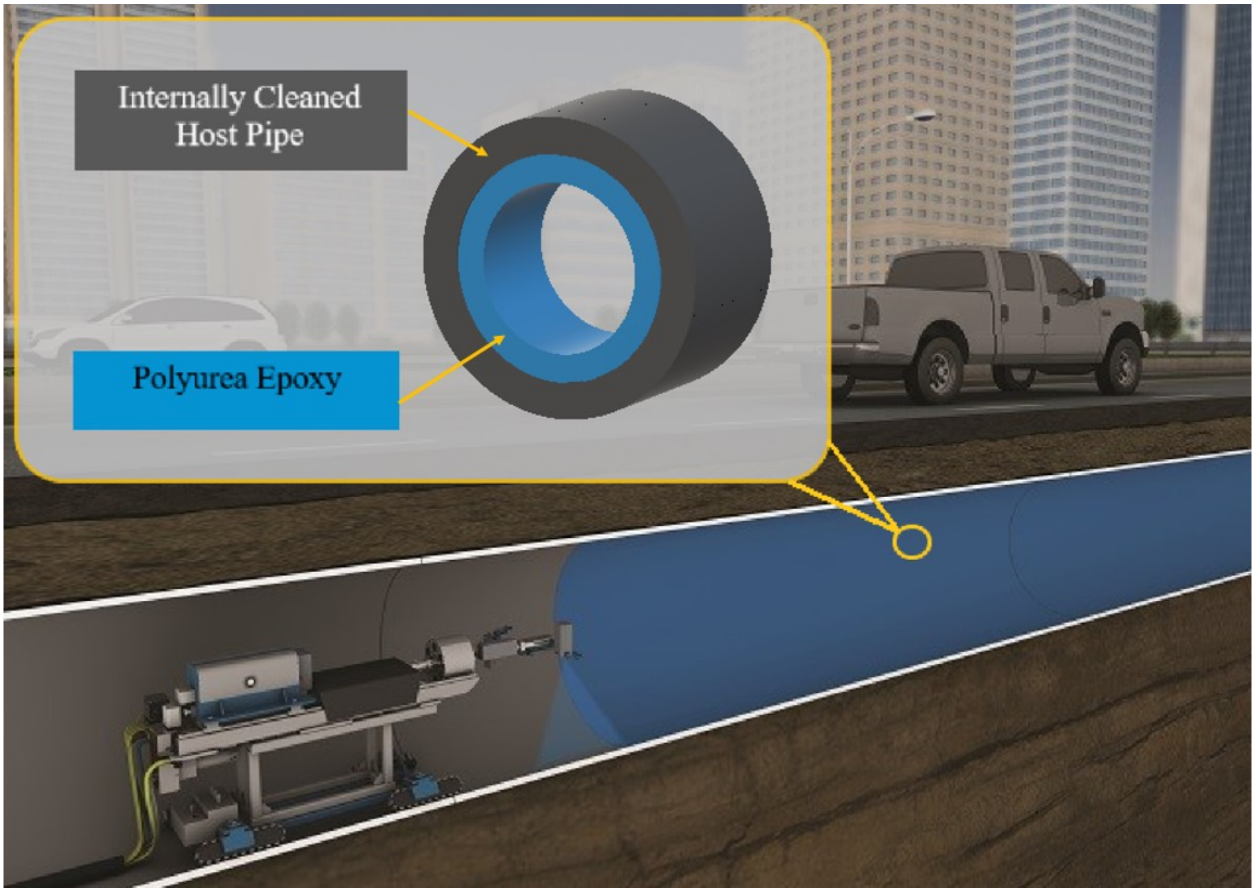

Figure 5. Spray-on Lining Process (adapted from http://www.canadianundergroundinfrastructure.com)

5.5.7 CIPP Lining Procedure

The installation of CIPP is much more complex compared to the spray-on method. Two installation procedures exist: inversion and pull in. Both are being widely used around the world. As shown in Table 21, different water main CIPP products are installed using the inversion and/or pull-in methods. The differences between the site operations of both types of installation are illustrated in Figure 6. Pulled-in method have the polyurethane coating on the inside of the liner during set up. In contrast, the coating will be setup on the outside of the liner while using inversion method. This polyurethane coating is resistant to hydrolysis and corrosion attacks, while providing smooth surface for friction reduction. Insituform products implements polypropylene, which has a longer product life compared with polyurethane. In contrast, each of the two installation methods requires significantly different processes and equipment; however, both techniques are equally beneficial for a project subject to the project requirement and site conditions (Lanzo Lining Services Inc., 2010). Such that when one major section of the pipe requires repairing or one access point is available, then pull-in method will be more useful. Meanwhile, the use of inversion will provide better control during the expansion of the liner, however it is best for larger diameter sized pipes (Lanzo Lining Services Inc., 2010). The most relevant method for installation will be selected to achieve the best result, as reviewed by Lanzo Lining Services (2010), each method will have its advantage in order to finish the project safely and on time, as well as within the required budget.

In the inversion method, high pressure of water or air will be applied to expand the folded liner physically into the desired host pipe circumference (ASTM F1216, 2016). Supposedly, same expansion options should be applied to pull-in method according to ASTM standard. However, based from field experiences, it is suggested that pull-in should uses pigs to expand the liner (Bontus, personal communication, 2018). For the inversion technique, a hydrostatic head will be introduced so the water pressure will be enough to invert the liner. Also, during installation, the liner will be inserted into the downpipe inside out, such that when the liner is inverted, the impermeable surface becomes the liner's internal surface (ASTM F1216, 2016).

In the pull-in technique, the main alteration is implementing a calibration hose for expanding the pulled-in pipe to the desired size. The resin saturated liner is pulled into the desired location with the outer coating on the outside, and then a calibration hose is inverted into the pulled-in liner, which is similar to the process of inverting the CIPP liner. The inverted calibration hose can be designed to be removable, so once the pulled-in liner is inflated and cured, the removable calibration hose will make no contact with resin and can thereafter be removed after installation is complete. Conversely, a non-removable calibration hose will become a part of the liner, where resin will be absorbed and the calibration tube will be cured and bonded tightly against the fabric tube (ASTM F1743, 2017). In addition, the pull-in method could also use pigging as the method of liner expansion, by push pigs through the liner using water or air pressure (ASTM F1743, 2017). In real market, BlueLine installation implements the standard suggested calibration hose expansion method, while for Aqua-pipe produced by Sanexen, pigging is used.

To cure the resin, heating devices are attached to both ends of the liner and host pipe for circulating hot water or steam through the section to cure the resin. Hot water is the most commonly used method for curing, as water is readily available and can be boiled in a boiler truck. To ensure an effective curing of the liner and resin, the ASTM standard suggest that hot water needs to be pressurized at the section of the pipe at 80°C for 90 minutes. If steam curing is used, the curing will require shorter duration since steam transfers heat faster than water. After the required curing time, the liner will be cooled to below 38°C (ASTM, F1216, 2016). In practice, however, the temperature and time duration of heating varies depending on different products, liner thickness as well as other onsite situations.

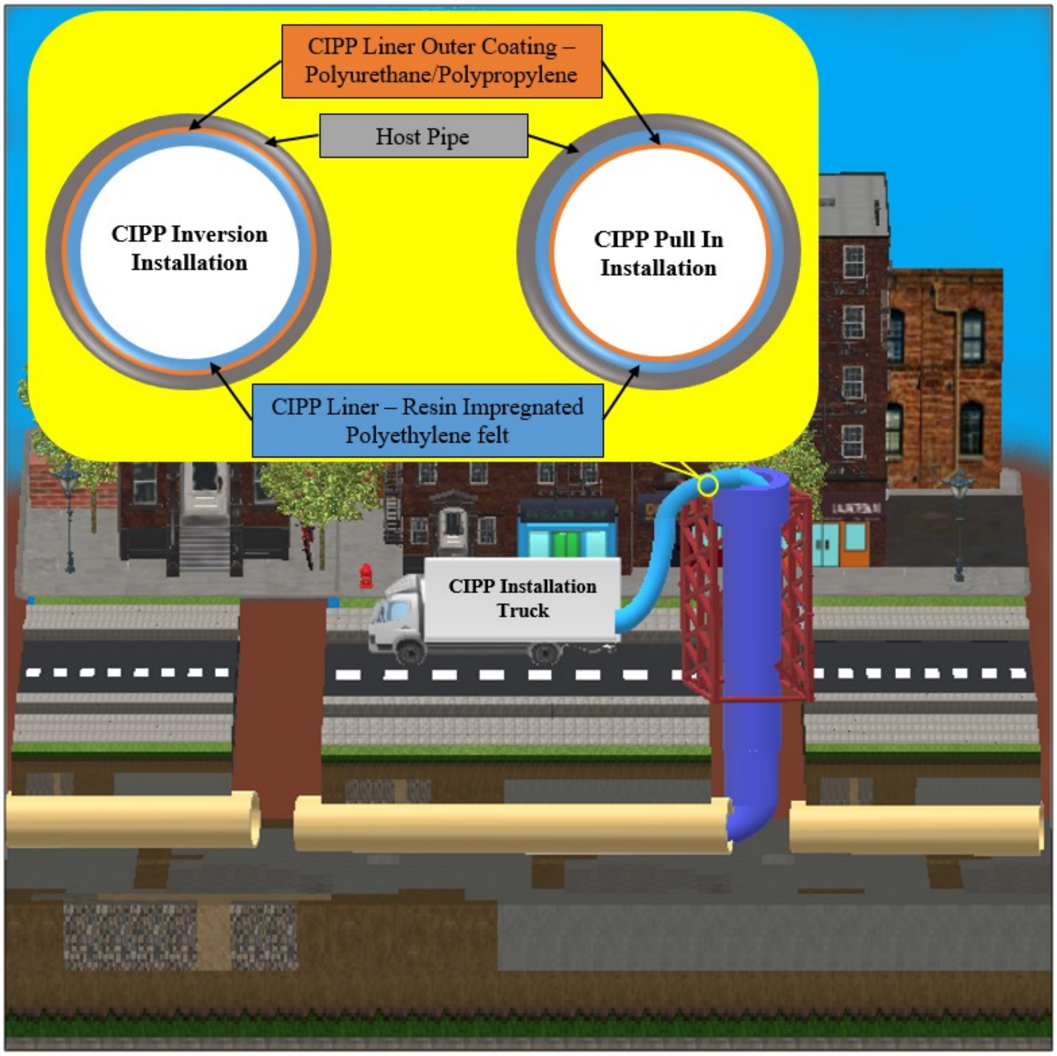

Figure 6. CIPP Pull-in and Inversion Installation Setup

The equipment and materials required to perform both processes are shown in Table 27. Reefer trucks are refrigerated trucks that contain the liner saturated with resin that is ready for installation. The CCTV camera and robot are often used to monitor and control the procedure remotely from inside the reefer truck. The liner can either be saturated at the manufactural location then moved to the site for installation, or it can be saturated onsite immediately before the installation depending on the project situation. Scaffolding is typically used in inversion installation to set up water column for pipes with diameter size between 12 to 16 inches, as the water head pressure will be required to invert the liner inside the host pipe. CIPP products are composite liners, where the woven polyester or fiberglass/felt layers allows penetration of resin through the liner, while glass fibre provides chemical corrosion resistance for the system. The epoxy resin or vinyl ester resin also provide resistance to corrosive chemicals and add strength to the liner after hardening, which supports the internal and external loads.

Table 27. Material and Equipment Involved During CIPP Installation

Material/Equipment	Pull In	Inversion
Tubes	√	√
Resin	√	√
Catalyst	√	√
Freight /Demurrage	√	√
Reefer Truck	√	√
Conveyor Reefer	--	√
Flusher/Vactor	√	√
Jetter/Water Truck	√	√
Picker Truck	√	√
Boiler	√	√
CCTV	√	√
Cutter Van	√	√
Pick-up Truck	√	√
Wet out Facility	√	√
Tool Trailer	√	√
Scaffolding	–	√
Compressor	√	√

5.6 Post-Lining Hydrostatic Pressure Testing and Service Reinstatement

Once lining is finished, a hydrostatic pressure test has to be conducted before service reinstatement is performed. This test ensures the makeup water or water lost due to evaporation and leakage does not exceed the amount permitted by local municipal requirement. After which, service connection reinstatement and post-lining CCTV inspection can be carried out. Using the recorded locations of the service connections during pre-lining inspection, the covered taps can be opened internally with the remotely controlled robot. However, instead of attached with plugging device, the robot is combined with an air drill bit for reinstatement purpose. Most often, the connections can be reinstated internally; nevertheless, if issues such as folds occurred at the service connection location, plugging failure during liner installation causes resin to block the connections, resulting in a misalignment of the plug and connections and external reinstatement will be required (Matthews et al., 2012). In which case, excavation at the service connection location will have to be executed, which results in extra work for the crew and longer project duration. While performing reinstatement through the lined pipe, CCTV inspection will be performed simultaneously, and the footage should be saved for record keeping.

5.7 Site Restoration

The cut-out portion of host pipe have to be reconnected once all installations and inspections are performed. Any instrumentation such as hydrants and valves that were involved in the installation also have to be replaced. The cut section of host pipe will be reconnected with new ductile iron pipes by flanges, which are coupled to the end flange of the host pipe. In order to ensure the safe connection, end seals should be installed. The end seals that each water main rehabilitation company implements are represented in Table 28. Aqua-Pipe, however, does not require end seals, and no issues were recorded in past projects during reconnection (John, 2015). Smaller sized pipe rehabilitation will not require flanges to be installed at the pipe ends, where a coupling will be able to connect the new pipe to the ends of the cut host pipe. For pipe sizes around 12 inches or above, flanges will occasionally be required for connection purposes. As soon as reconnection is ensured, construction restoration is required before the project is finished and the pipe is ready for operation. The restoration requires back filling of the excavated pits, as well as restoring any damaged pavement or grass according to environmental regulations.

Table 28. End Seal Requirement of Each CIPP Rehabilitation Companies

Company Name	Product Name	End Seal Requirement
Sanexen Water Inc.	Aqua-Pipe	Not Required
Insituform/Aegion	Insitumain	Mechanical Expansion Type NSF 61 Approved (FRP Coupling & Fiberglass Spool)
Sekisui	Nordipipe	WEKO-Seal (NSF/ANSI 61 Approved product)
HammerHead and RS Technik (Pipe Aquatec)	BlueLine	Mechanical Expansion Type NSF 61 Approved

5.8 Chapter Conclusion

Ever since the development of rehabilitation technologies, the advancement of these technologies has been growing rapidly over the past century. The four major corporations providing CIPP product and installation have been using products that are approved by NSF/ANSI Standard 61 for safe potable water delivery. Many other companies also have the technologies and products, however, are much smaller in scale.

The minimum thickness design for current water main CIPP liners are using sewer pipe rehabilitation standards, where the maximum pressure and pressure surge of the water mains are not considered. Furthermore, the CIPP installation procedure for the water mains were not addressed for current standards. The installation is different with sewer and water mains, where access pits will be required, as well as service by-pass will be required.

There are four categories of structural classification of liners, where Class I for non-structural repairs, Classes II and III for semi-structural repairs, and Class IV for full structural repairs (AWWA, 2014). Current CIPP products are generally fully structural liners, where spray-on liners are classified as non-structural repair. It is suggested by spray-on companies that spray-on can be used for semi-structural or full structural rehabilitations, however, based on real life projects, it is not ideal to apply spray-on liners on pipes that requires other than Class I repairs(Bontus, Personal Communication, 2019).

From the review of rehabilitation methods in previous researches and standards, it is clear that rehabilitation methods are a very well developed and easy to use method for water main renewal. It does not only cost less compared to open cut or other replacement methods but will also make the construction way easier in more populated areas. In addition, the overall performance of the mains after rehabilitation will provide same if not more structural stability. As a result, it is strongly recommended to the municipalities to start implement more rehabilitation methods as an alternative to open-cut or replacement methods.

Chapter 6: Generalizing Tests for Water Main Rehabilitation Process and Associated Risks

6.1 Introduction

Quality control and quality assurance usually comes together as a whole process to ensure the design meet the safety requirements. However, quality control and quality assurance are distinctly different processes. Quality assurance looks into the bigger picture of the overall process (Macey, 2018). This consists of a series of looting steps that include define, measure, analyze, improve, control then back to define. Each of the steps has to be confirmed in order to ensure the overall assurance is met. For CIPP rehabilitation projects, from design to wet out, installation, cure, post installation inspections, sample collection and testing, each phase have to be carried out safely to be considered a successful QA/QC process. Quality control instead is used to verify whether a design of product is in an acceptable quality. It involves activities such as mechanical tests and measurements. Nonetheless, without one another, the practice of a safe design cannot be ensured.

With the evolution of water main rehabilitation products and successful project completion around the world, the accomplishment has helped this technology to gain great success in the water sector market. Even though minimal safety risk is present with this technology, issues and challenges related to the water main system rehabilitation still exists. Bonding between liner and host pipe cannot be checked after installation unless a section of pipe is taken out of service for lab test, also there has not been a standard that is specifically developed for pressurized water main rehabilitation. These facts restricted the growth of CIPP technology and leave considerable room for improvements.

In addition to the lab tests for checking the structural performance of the liner, also there are short- and long-term monitoring methods available for water main CIPP rehabilitation projects. However, these methods are not often performed as it is not efficient in practice, or it will increase the project cost significantly.

6.2 Existing Tests

Applicable field and lab tests for evaluation of the product and installation after lining are listed in Tables 29, 30 and 31; along with the corresponding industrial standards for each of the tests. These tests are part of the QA/QC of the general CIPP rehabilitation standards (Muenchmeyer, 2007); however, most often the listed tests were not performed for every regular installation since many of the tests significantly increases the project cost. Hydrostatic pressure test will always be performed after any rehabilitation project to ensure the mechanical performance of the liner follows the requirements. The other most common physical test implemented after rehabilitation is thickness measurement of liners that can be reached at the access pit.

6.2.1 Site Investigation and Water Sample Tests

One of the important pre-lining tests that can be performed before every project start is the assessment of the surrounding ground conditions. This process ensures construction can be safely performed and allows the liner provider to better understand the cause of the current condition of host pipe, such that full risk mitigation can be evaluated ahead of the project. Soil sample tests will provide information about soil properties, as well as the rate and extent of the corrosive behaviour of the soil (Matthews et al., 2012). However, it can be included as part of the condition assessment. Water sample collection and testing is a regulated procedure to ensure the potable water after installation can be safely delivered for everyday use (AWWA C651, 2014).

Table 29. Site Investigation and Water Sample Tests

Test Methods	Description	Standards and References
Soil Sample Testing	Collect soil samples around the pipe	ASTM C-136 (Particle Size) ASTM D-4959 (Moisture Content) ASTM D-4972 (pH) ASTM G-187 (Electrical Resistivity) ASTM C-1580 (Sulfate Concentration) ASTM G-200 (Oxidation Reduction Potential) EPA 9080 (Cation Exchange Capacity) EPA 9030B (Sulfide Concentration) EPA 9250 (Chloride Concentration)
	Test the soil properties and corrosivity potential	
	Evaluate the rate and extent of corrosion to host pipe	
Water Sampling	Collect water sample prior and after rehabilitation	AWWA C651 AWWA M12
	Ensure the water quality is acceptable according to standards	

6.2.2 Post Lining In-situ Tests

After lining is complete, the tests that are required to be performed are listed in Table 30. These tests are to ensure the installation of the liner is completed correctly according to design specifications. Hydrostatic pressure tests ensure the lined pipe can provide service without further water leakage. Hydraulic testing makes sure that the condition or quality of the internal surface of the rehabilitated is satisfactory and the pipe is cleared from further obstructions. This test, however, is rarely done in real installation. Lastly, measurements of liner thickness will help to assess the quality of liner product and installation by comparing with the designed thickness.

Table 30. Post-Lining Field Tests

Test Methods	Description	Associated Standards
Hydrostatic Pressure Test	Pipe pressurized with water to two times operating pressure or operating pressure +50 psi	ASTM F1216 ASTM F1743 Alzraiee et al., (2013)
	Pressure gauge to monitor pressure for one hour	
	Ensure the makeup water or water lost due to evaporation and leakage does not exceed the amount permitted, which is 1L/hr/280ft of length	
Hydraulic Testing	Hazen-Williams C-factor to determine the amount of pressure loss caused by friction	Matthews et al., (2012) Allouche et al., (2011) Alzraiee et al., (2013)
	C-factor should be at least 120	
Liner Thickness Measurement	Measure with caliper or ultrasonic device to evaluate if liner thickness after installation matches design thickness, typically done with restrained sample	ASTM F1216 ASTM F1743 Alzraiee et al., (2013)

6.2.3 Material Lab Tests

The lab tests listed in Table 31 are possible tests to be performed on the liner product and the composite of liner and host pipe. These tests are QA/QCs to ensure the water main liner is satisfactory or beyond the basic design standards. Flexural, tensile, compression, buckling, negative pressure, as well as pressure design tests are strength related tests to evaluate the liner performance after installation (Awe, 2017), where values obtained should be equal to or above the manufacturer design values. Peel, puncture, liner ovality, hardness, and Raman spectroscopy tests are complimentary tests to assess that the product is well beyond required performance.

Table 31. Summary of laboratory tests to evaluate the performance of liner

Category	Test Methods	Description	Standards and References
Strength Related Tests	Flexural Test	Determine the flexural strength of liner product using three-point loading system until the liner sample yield or break	ASTM D-790 Knight, (2006) Herzog, (2007) Riahi, (2015)
		Peak bending stress and flexural modulus should be higher than design value	
	Tensile Test	Determine the tensile strength of liner product by stretch the sample until yield or break	ASTM D-638 Knight, (2006) Herzog, (2007) Riahi, (2015)
		Tensile peak stress should be higher than design value	
	Compression Test	Determine the deflection characteristics of liner or liner with host pipe under parallel plate loading	ASTM D-2412 Herzog, (2007) Riahi, (2015)
	Short Term Burst Test	Determine the deformation or failure characteristic of liner by applying pressure all around simulating the in-situ condition	ASTM D-1599
	Negative Pressure Testing	Determine the deflection of liner when the pipe internal is vacuumed with negative pressure	Matthews et al., (2012) Allouche et al., (2011)
	Hydrostatic Design Basis	Determines hydrostatic long-term design basis with evaluation of strength regression of liner and host pipe	ASTM D2992
Complimentary Tests	Peel Test	Determine the peel or stripping characteristic of adhesive bonds of epoxy resin	ASTM D-903
	Immersion Test	Determines the coating for steel water pipeline 's response when submerged in deionized water, weak acid, and weak base	Awe, (2017) AWWA C210
	Puncture Test	Determine the shear strength of liner before saturated with resin	ASTM D-732
	Liner Ovality Test	Determine the ovality after buckling test if it is within 5% allowable maximum ovality	Matthews et al., (2012) Allouche et al., (2011)
	Hardness Testing	Measure the penetration of specified indenter into the liner material	ASTM D-2240
	Raman Spectroscopy Test	Assess liner material's degree of aging	Matthews et al., (2012) Allouche et al., (2011)

6.3 Risks and Challenges

Correctly determining the condition of a buried pipe is a challenging but essential phase before performing the rehabilitation process. With the current technology, the only way to understand the condition of the old pipe is to monitor the outflow of water quality. If the condition of the deteriorated pipe is critical, it may not be possible to implement CIPP lining. Instead, replacement with new pipe will be required. Even if the pipe can be repaired with CIPP, the degree of deterioration and major defects should be noted for the installation crew. Additionally, geotechnical report of the area, as well as the surrounding site condition and nearby utilities are also factoring that should be determined at the design stage (Selvakumar et al., 2012).

Each step of the CIPP installation in water main pipes has its own risks. Many of these risks are unavoidable with the current technology, as they apply to all rehabilitation methods, while some issues such as liner product, resin, and installation and curing methods; that are used in CIPP installation, can be gradually improved (Rogers and Louis, 2007). In water rehabilitation projects, more than one day is required to complete the installation before water services may be switched back on. During this time, service by-passing has to be set up to provide potable water for directly impacted areas. This step is expensive, and the quality of the water supply has to be ensured. Access pit excavation and site restoration are procedures mandatory despite the method used for replacement or rehabilitation, since no access points are available for water mains. After the pull-in and curing process, the resin not capable of bonding the liner to the host pipe is a potential risk that all companies tries to mitigate. Other issues include folds, which will cause difficulty during the service reinstatement process and impact pressure capability of the liner, misalignment of the cap and connection, and resin penetration through the plug cause blocking (Jaganathan et al., 2007). Potable water pipes have hundreds of service connections along one line providing water to households and buildings. Even though the development of remote-controlled CCTV and internal reinstatement robotic technology helped to improve the efficiency of renewal process, issues still arise, and the service connections may have to be reinstated externally. According to Selvakumar et al., for water main projects, around 5% of service taps had to be reinstated externally due to challenging circumstances (Selvakumar et al., 2015). However, during actual installation, about 50% to 90% has to be reinstated externally (Bontus, personal communication, 2018). Consequently, if external reinstatement can be minimized during the installation, lower costs and shorter project duration can both be achieved. Since excavation will be required for external reinstatement, this increase the duration of the project and will require longer work hour from contractors, which in turn results in higher cost as well.

The lack of CIPP long-term performance verification tests is another potential risk, where liner after years of deformation and wearing is often not retested to checking its condition. In addition, there is no existing standard for the baseline qualification of testing after lining installation (Matthews et al., 2012). The QA/QC procedure have to be enhanced for using CIPP rehabilitation on water main r projects, and the entire service life of the liner needs to be assessed and information collected in the field from all the stages are important (Selvakumar et al., 2012).

Most of the listed risks and challenges happened during the design and installation, can be mitigated by being cautious and conducting detailed QA/QC processes, while risks due to technological limitation can only be minimized through further research and development. Some issues related to existing CIPP installation are unavoidable with the current technology, such as water by-passing, access pit excavation, as well as service reinstatement. Meanwhile, challenges for determining soil condition, pipe condition, surrounding infrastructures, and risks of misalignment of capping and connection after installation, or resin causing service pipe blockage, are challenges that can be alleviated through attention to detail. Such that, detailed geotechnical reports and pipe condition reports should be obtained first, also better plugging products and services need to be developed. The lack of long-term performance monitoring and testing, as well as baseline standards, are systematic risks that will only be improved through more years of data collection and analysis (Shahata and Zayed, 2012).

Table 32. Risks Associated with Liner Installation Stages

Lining Stages	Activities	Risks or Challenges	Mitigation Plan	References
Pre-Lining	Pre-lining In-situ Assessment	Failure to determine the condition correctly will lead to construction obstruction	Careful assessment	Selvakumar et al., (2012)
	Service By-Passing for CIPP Installation	Expensive and water quality has to be ensured	Research on possible replacement method (faster installation)	Rogers and Louis, (2007)
	Access Pits Excavation	Effect on other utility lines during excavation	Careful excavation should be performed	Selvakumar et al., (2012)
Lining	Lining Process	Bond between liner and host pipe is weak, misalignment of capping and connection cause resin blockage of service connections	Better QA/QC during service capping and lining process	Selvakumar et al., (2012)
Post Lining	Post Lining Inspection	Lack of long-term performance verification tests	Establish research and testing on the long-term performance of liner, also set up monitoring methods	Shahata and Zayed, (2012)

6.4 Suggested Monitoring Methods

One method for monitoring whether or not the rehabilitation was effectively installed is to perform an ultrasonic examination using smart pigging technology (Varela et al., 2014). This technology can map the internal surface of the pipe before and after the lining and detect the gaps between the liner and host pipe using ultrasonic radiation. If required, smart pigging and the corresponding software system will automatically provide information and process an analysis of the pipe condition so the bond performance can be easily reported (Bickerstaff, 2002). The disadvantages of using smart pigging for performance testing is the cost and its practicality. A test pipe section with 100m in distance costs more than $100,000, which is not cost effective (personal communication, 2018). Nonetheless, smart pigging can be a great in-situ test for future projects if the cost issue can be resolved.

Installation of sensor gauges between the liner and the host pipe is another potential monitoring method for future projects. Sensors have to be able to withstand high pressure and temperature in order for data to be effectively collected. At least four sensors should be set up with equal spacing along the perimeter of the pipe, and each set of sensors should be installed at a designated length in order for a comprehensive collection of data, which can be used to analyze the deformation between liner and host pipe. The restriction, however, is that most sensor gauges are wired and will have to be connected to a transmitter in order for the data to be collected by the researcher or lab technician, but existing transmitters are often too large to be installed. Furthermore, the bond may fail over time at locations where strain gauges are installed. Fibre optical sensors are a solution that may be practical to install inside the liner to monitor the long-term deformation of the product (Giallorenzi et al., 1982). This technology is widely used in the oil industry, in addition to strain and deformation monitoring, it can withstand high pressures and high temperatures, detect drops in temperature or pressure, as well as detect acoustic vibration due to leakage or burst over a long distance continuously (Grattan and Sun, 2000). As long as the fibre optical sensor is tightly installed against the internal surface of the liner, this technology can be an effective monitoring method (Ramakrishnan, 2016).

6.5 Chapter Conclusion

The quality control and quality assurance are an essential process in ensuring safe delivery of projects, where field and lab tests on liner performance should be conducted. The challenge with these tests is the high cost and time consumptions, therefore, they are not implemented on a regular basis. Furthermore, the lack of baseline and long-term evaluation of liner performance should be focused for future researches, such that by collet more data and use them to perform numerical modeling, many of the risks and challenges could be mitigated.

Chapter 7: Summary and Conclusions

Five key finding of this thesis are summarized below:

1. The water system condition cannot be fully understood through observation or observation.
2. Pipe material made of Ductile Iron and Cast Iron are having more issues or in poor condition in the water systems compared to other material, especially in the transmission systems with pipe diameter between 6” to 12”.
3. Replacement methods using open-cut is still the primary technique for pipe renewal in cities with broader land are, while for cities with more condensed population implements CIPP trenchless technology and open-cut to a same degree.
4. Using rehabilitation method for water pipe renewal can save up to more than half the cost amount compared to replacement method.
5. Project cost is not one of the priorities affecting utility provider’s decision in choosing the method for pipe renewal, product life is a more important factor while making decision on which type of method to use for pipe renewal.

Based on the data collected through survey questionnaire, the four surveyed city water main system were examined in depth. In terms of material, the major concerns are mostly on Cast Iron and Ductile iron pipes, which had lower condition ratings. While for pipe systems, distribution system has the highest failure factor with most of the breakage occurring. In general, failure rating for the four surveyed cities is between 0.6 to 1.5 breaks per kilometer per year. One of the cities has a failure rating of 0.2 breaks per kilometer per year. In addition, the failure factor for different materials were also analyzed as an index for determining material conditions in different cities. It was concluded that water pipe material made of Ductile Iron and Cast Iron are having major issues in all four surveyed cities, especially in the transmission systems with diameter between 6” to 12”. Through the identification of these found issues in the water main system, the analyzed results such as failure rating can be useful for utility providers to consider. It can also be used as reference to compare with future surveys.

From the survey, all cities reported to use certain condition assessment technology and methods for evaluating the water mains conditions. Of which, acoustic sensors are the most commonly used technology out of many others, while number of breaks is the most common method for evaluating the pipe condition. After comparing between replacement and rehabilitation methods implemented by different cities in the past years, CIPP was the most popular rehabilitation methods used, where open cut method was the primary method used for replacement. In cities where population are condensed, and areas have more compact infrastructures above ground, length repaired using replacement and rehabilitation methods were relatively equal. Otherwise, replacement method is still the main method used in other cities. The unit cost is generally lower for rehabilitation methods while compared to replacement, also as the pipe diameter increases, the unit cost for replace or rehabilitate will also increase. Each city had a planned annual budget for their water system renewal using different methods. Replacement method had the leading annual budget compared to rehabilitation. The decisions of choosing between rehabilitation and replacement method for pipe renewal, as well as planning a corresponding annual budget depends on various factors and concerns. One of the most important factor utility providers are looking for was “product life”. Through this survey questionnaire, with more data collected from responses by other water utility providers in the future, a more comprehensive analysis and understanding of the water industry will be achieved. Henceforth, both utility providers, as well as rehabilitation and replacement contractors will be able to make effective and accurate decision on how to mitigate water main issues prior to their occurrence.

Overall, the survey performed for this thesis is a pilot survey, which means there are still large areas for improvement in future actual surveys. From the survey, it was obvious that many areas have the potential for improvement to make the data more comprehensive and reliable. Minor discrepancies in data as well as lacking range of data are presented in this survey. Where some of the discrepancies are caused by the insufficient information the participants on their water system information, which can only be improved through more data collection in the future across the country to make the data more reliable. Other minor data collection errors are caused due to the nature of the survey, as the survey implements mostly using multiple choice to save answering time, where places such as the total does not add up to 100% was due to the selection range. Such that the range of data choices should be increased to higher range to implement more accurate data collection, if possible, input of information could also be introduced instead of selecting from the given range choices. Also, the survey could implement more questions in the content to obtain other areas such as how often the water mains are assessed for QA/QC using technologies such as smart pigging and NDT. Furthermore, which pipe diameter ranges or type of locations are being assessed more than others. Most importantly, the more the data obtained in the future surveys, the more reliable the result can be used for industrial considerations.

Considering the survey results, CIPP and spray-on methods have a relatively lower unit cost making rehabilitation more ideal compared to open cut. In general, the water main rehabilitation market has been gaining attention from many countries around the world. Instead of performing open trenching to replace water infrastructure with the new pipes, methods such as CIPP liner and spray-on polymer liner installation have been largely accepted by local governments worldwide. The four major water main CIPP manufacturers and service providers, Insituform, Sanexen, RS Technik, and Sekisui, have presented their products approved by NSF/ANSI Standard 61 to be used for potable water pipe rehabilitation. Current water main CIPP liners' minimum thickness are designed using the associated ASTM standard for sewer pipes, which only accounts for low internal pressure. This standard for sewer liner design neither account for the water pressure surge in the pressurized water main pipes, nor account for the pressure surge limitation. In addition, the installation procedures for water mains was not addressed within the available standards.

In summary, the main issue to be addressed as for now based on the survey results is to perform pipe renewal on Ductile Iron and Cast-Iron pipes. With the implementation of water main rehabilitation using CIPP methods on aging potable water pipelines could potentially improve the water main system significantly. In fact, trenchless rehabilitation technologies can improve pipe renewal work with faster construction periods, less social impact to local communities, as well as lower the project costs if planned and executed carefully.

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APPENDIX I

WELCOME!

You have been selected to respond to a survey developed by CETT researchers at the University of Alberta on Water Main Condition Assessment and Rehabilitation. By completing this survey, you will assist us in analyzing the current state of water systems and evolving trenchless technology accordingly to improve rehabilitation processes to meet both short-term and long-term needs.

Background:

This survey forms part of an overall research project entitled “Advancing Water Main Renovation and Design” focused on investigating methods to renew aging and failing water main infrastructures quickly and effectively. The primary objective of this research is to advance knowledge related to trenchless rehabilitation methods, particularly to address issues in extending the application of cured-in-place-pipe (CIPP) to rehabilitate water transmission/distribution systems.

Win an Apple Watch Series 4!

By filling out and submitting this survey, you will be automatically entered in a draw to win an Apple Watch Series 4. The draw will take place on May 10, 2019.

Note:

This survey is a pilot version for testing purposes, with limited distribution. Your participation in testing the survey and giving feedback is appreciated.

This survey contains a total of 24 questions as well as some information responses over seven pages, and is expected to take approximately 25-30 minutes to complete.

The survey is organized as follows:

Section 1 – Water Distribution/Transmission Network
Section 2 – Condition Assessment
Section 3 – Rehabilitation

Responses are saved and submitted when the Next button is clicked at the end of each page. Any responses saved (by clicking on Next) can be edited at a later time, until the complete survey is submitted.

To download the survey information, click here. To download the complete survey in .pdf format, click here.

Consent Statement

* 1. I have read this form and the research study has been explained to me. I have been given the opportunity to ask questions about the survey. I have been told who to contact to withdraw my responses (up to 30 days after submission of the survey) or if I have any additional questions. I understand that by completing and submitting this survey, I have given consent for the data I have provided to be used for the purposes of this study, as described in the information provided.

Note: To download the survey information form, click here.

Unit System

* 2. Please indicate the unit system used for your utility

Section 1: Water Transmission/Distribution Network

3. Please indicate the estimated range of lengths for the corresponding pipe diameters/water system.

Distribution, 6" to 12"	
Transmission, >12" to 24"	
Transmission, >24"	

4. Please indicate the estimated range of operating pressure for the corresponding pipe diameters/water system.

Distribution, 6" to 12"	
Transmission, >12" to 24"	
Transmission, >24"	

5. Please indicate the estimated range of depth of cover for corresponding pipe diameters/water system.

Distribution, 6" to 12"	
Transmission, >12" to 24"	
Transmission, >24"	

6. Please select the estimated percentage (by length of pipe) for each pipe material corresponding to your water system.

Note: The percentage for each system should add up to a total of 100%. Pleaseleave blank if the material is not used in the system.

	Distribution System, 6" to 12"	Transmission System, >12" to 24"	Transmission System, >24"
Cast Iron			
Ductile Iron			
Asbestos Cement			
PVC			
HDPE			
Steel			
Fiber Reinforced Plastic			
Pre-stressed Concrete Cylinder (PCCP)			
Concrete Pipe			
Other			

Please specify

7. Please rate the current overall condition of your organization's **Water Distribution System, 6" to 12"** for each pipe material based on your understanding of the system.

Note: Please leave blank if the material is not used in the system or the information is unknown.

	Very Poor	Poor	Tolerable	Good	Excellent	N/A
Cast Iron						
Ductile Iron						
Asbestos Cement						
PVC						
HDPE						
Steel						
Fiber Reinforced Plastic						
Other						

8. Please rate the current overall condition of your organization's **Water Transmission System, >12" to 24"** for each pipe material based on your understanding of the system.
Note: Please leave blank if the material is not used in the system or the information is unknown.

	Very Poor	Poor	Tolerable	Good	Excellent	N/A
Cast Iron	○	○	○	○	○	○
Ductile Iron	○	○	○	○	○	○
Asbestos Cement	○	○	○	○	○	○
PVC	○	○	○	○	○	○
Concrete Pipe	○	○	○	○	○	○
Pre-stressed Concrete Cylinder (PCCP)	○	○	○	○	○	○
HDPE	○	○	○	○	○	○
Steel	○	○	○	○	○	○
Fiber Reinforced Plastic	○	○	○	○	○	○
Other	○	○	○	○	○	○

9. Please rate the current overall condition of your organization's **Water Transmission System, >24"** for each pipe material based on your understanding of the system.
Note: Please leave blank if the material is not used in the system or the information is unknown.

	Very Poor	Poor	Tolerable	Good	Excellent	N/A
Cast Iron	○	○	○	○	○	○
Ductile Iron	○	○	○	○	○	○
Asbestos Cement	○	○	○	○	○	○
PVC	○	○	○	○	○	○
Concrete Pipe	○	○	○	○	○	○
Pre-stressed Concrete Cylinder (PCCP)	○	○	○	○	○	○
HDPE	○	○	○	○	○	○
Steel	○	○	○	○	○	○
Fiber Reinforced Plastic	○	○	○	○	○	○
Other	○	○	○	○	○	○

10. Please indicate the estimated range of years that each service connection material began to be utilized in your system and the range of years that it stopped being used.
Note: Leave blank if the material was not used or the information is unknown.

	Start Date Range	End Date Range
Lead		
Copper		
Galvanized		
PVC		
HDPE		

11. Please select the estimated range of percentages for each of the following pipe material where **Direct Tap** and **Service Saddle** methods were used for service connections, respectively
Note: For each method, the percentages given should add up to a total of 100%. Please leave blank if the material is not applicable.

	Direct Tap Method	Service Saddle Method
Cast Iron		
Ductile Iron		
Asbestos Cement		
PVC		
Concrete Pipe		
PCCP		
HDPE		
Steel		
Fiber Reinforced Plastic		
Other		

Please specify

12. Please provide the estimated total water use per capita (gallons/capita/day) if known.

13. Please select an estimated percentage range of overall unaccounted water (water loss) for each of these pipe service types in your utility.

Distribution, 6" to 12"	
Transmission, >12" to 24"	
Transmission, >24"	

14. Please provide the total estimated number of water main breaks that occurred throughout your water system in the past year.

15. Out of all the breaks that occurred in your system throughout the past year, please select the estimated percentage of breaks for each of the following pipe materials in your water systems.

Note: The percentage for each system should add up to a total of 100%. Please leave blank if the material is not used in the system or the information is unknown.

	Distribution System, 6" to 12"	Transmission System, >12" to 24"	Transmission System, >24"
Cast Iron			
Ductile Iron			
Asbestos Cement			
PVC			
PCCP			
Concrete Pipe			
HDPE			
Steel			
Fiber Reinforced Plastic			
Other			

Please specify

Section 2: Condition Assessment

Condition Assessment refers to all activities that are employed to assess whether the overall quality of existing water mains are sufficient and suitable for delivering safe potable water to the respective system, or whether repair/rehabilitation methods will be required.

16. Please indicate whether you have undertaken any water main pipe condition assessment, monitoring and detection methods using advanced technologies to determine the status of your system.

- ○ Yes
- ○ No

17. If yes, please select any or all types of leak detection methods that have been used for condition assessment.

- ☐ Acoustic Sensors
- ☐ Ultrasonic wall thickness testing and monitoring
- ☐ Smart Pigging
- ☐ Hydro-static Testing
- ☐ Thermographic NDT
- ☐ Laser Shearography NDT
- ☐ Other

Please specify

18. If no, please select any or all other factors that are used for determining the condition of your system.

- ☐ Number of Breaks
- ☐ Water Quality (odor, color, etc)
- ☐ Age of pipe
- ☐ Hazen–Williams C-Factor Calculation
- ☐ Other

Please specify

19. Please provide the **number of failures per year** that occur on your system before replacement or rehabilitation.

Section 3: Rehabilitation

20. Please select the estimated percentage (over the length of the entire operating pipe) for the following systems that requires immediate repairs.
Note: Percentages should add up to no more than 100% for each system.

Distribution, 6" to 12"	
Transmission, >12" to 24"	
Transmission, >24"	

21. Please select the estimated length or range of lengths of pipe repaired in your water system over the past years using **rehabilitation** methods (e.g. CIPP, spray-on lining, sliplining).
Note: Leave blank if information is not known.

	Past Year	Past 2 Years	Past 5 Years
Distribution, 6" to 12"			
Transmission, >12" to 24"			
Transmission, >24"			

22. Please select the estimated length or range of lengths of pipe repaired in your water systems over the past respective years using **replacement** methods (e.g. open-cut, pipe bursting, HDD).
Note: Leave blank if information is not known.

	Past Year	Past 2 Years	Past 5 Years
Distribution, 6" to 12"			
Transmission, >12" to 24"			
Transmission, >24"			

23. Please estimate the percentage for each restoration method used on your various water systems, out of the overall restorations performed on that system.

Note: Percentages should add up to 100% for each system.

	Distribution System, 6" to 12"	Transmission System, >12" to 24"	Transmission System, >24"
Open-cut			
Pipe Bursting			
HDD			
Spray-on Lining			
Sliplining			
CIPP			
Other			

Please specify

24. Please rank the following factors affecting decisions regarding the rehabilitation or replacement method to be used, in order of their importance.

1 = Most Important, 10 = Least Important

Note: If factors are of equal importance, the same rating can be applied.

Project Cost	
On Site Duration	
Minimal Disruption/Down Time	
Product Life	
Possible Onsite Uncertainties	
Availability of Contractor	
Contractor Technical Comfort Level	
Standard Design and Construction Guideline	
Location (Rural vs. Urban, Ground Conditions)	
Environmental Impact	

25. Please select the estimated average unit cost for the different repair methods used in your water systems.

	Distribution System, 6" to 12"	Transmission System, >12" to 24"	Transmission System, >24"
Open-cut			
Pipe Bursting			
HDD			
Spray-on			
Slip Lining			
CIPP			
Other			

Please specify

26. Please select the estimated annual budget spent on **Rehabilitation & Replacement Methods** for your water systems

	Rehabilitation Methods	Replacement Methods
Distribution, 6" to 12"		
Transmission, >12" to 24"		
Transmission, >24"		

General Municipality Information

27. Water Utility Name

28. Country

29. Province or Territory

30. State

31. Municipality – City/Town

32. Estimated Population Served

33. Please provide your contact information below.
Note: You do not need to provide contact information; however, this will allow us to contact you if you win the draw, and/or if you would like to receive a copy of the results of the survey (in publication form).

Name

Company

Email Address

Phone Number

34. Please indicate if you would like to receive the results of the survey (publication form).
Note: If you check yes, please provide your contact information in Question 57 above.

- [ ] Yes
- [ ] No

35. Please answer the following skill-testing question. Note that by providing your answer, you are confirming your eligibility for the draw.

5 × 2 + 5 =

36. How did you hear about this survey? If this survey was recommended to you, please give their name and company.

37. Please provide us with any additional comments you have related to this survey.

Survey Complete!

Thank you for your participation in the Water Main Condition Assessment and Rehabilitation Survey! We greatly appreciate your time, and look forward to sharing the results of this research!