# Evaluation of Cured-in-Place Pipe Lining Installations

**by**

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# ABSTRACT

Renewal of damaged and worn pipes is becoming a significant maintenance concern for municipalities in North America as many collection systems (water and wastewater underground infrastructure) have reached beyond the ends of their service lives. Cured-in-place pipe (CIPP) rehabilitation is one of the most common trenchless technologies, allowing users to renew existing underground pipes without using open cut methods. However, relining of large diameter sewer mains is not a straightforward process, and it is associated with a number of obstacles and deficiencies that lead to significant cost impacts to trenchless industries. This research provides a systematic review on the issues and challenges associated with CIPP rehabilitation projects of sewer mains, water mains and service laterals. Common problems and challenges are first reviewed from available literature and CIPP installation site visits. These obstacles and risks are classified into five different categories: pipe condition and configuration, pre-installation, challenges during installation, post-installation, and environmental challenges. In addition, this study discusses relevant measures adopted in current practices to mitigate these challenges.

Although productivity is the most significant factor for the planning and budget allocation of CIPP projects, there is limited information on the topic in literature. This study describes the CIPP process and conducts a productivity analysis of more than 40 sewer mainlines in Edmonton, Alberta, rehabilitated through the CIPP inversion process. The collected data includes inspection surveys of liner installation processes in sewer mains of varying lengths, diameters, and pipe materials. This research illustrates how varying pipe diameter and liner thickness affects productivity of the CIPP lining process. It is anticipated that this study’s results will contribute to more accurate estimations of CIPP project productivity, thereby helping with effective CIPP rehabilitation project planning and management.

Furthermore, for a lateral CIPP rehabilitation process, selection of an appropriate construction set-up for a project, such as crew and equipment conformation, is one of the challenges of the construction planning stage. It is essential to choose a suitable method that can save costs, time, and avoid significant disruption in the area, especially for projects in urban settings. Management must consider possible resource combinations (crew and equipment), test various construction scenarios, calculate the associated cost and time for each scenario, and determine the most desirable solution. In this research, a simulation-based approach was used to assist decision makers in choosing the best crew and equipment combination for lateral rehabilitation using CIPP from the mainline, also denoted by ASTM F2561 as lateral relining process using main and lateral cured-in-place liner (MLCIPL). A discrete event simulation model was developed for the lateral CIPP rehabilitation process. The simulation model enables users to apply different resource combinations and calculate the total duration of the project. The comparison of results is demonstrated in this thesis. This research also suggests an amendment to the installation sequence to improve the construction productivity, which was developed from the results of this model.

# PREFACE

Articles submitted to refereed journals/conferences

1. Das, S., Bayat, A., Gay, L., Salimi, M. and Matthews, J. (2015). A Comprehensive Review on the Challenges of CIPP Installations. *Journal of Water Supply: Research and Technology – AQUA*, Under Review.
2. Das, S., Navab, R. and Bayat, A. (2015). Productivity Analysis of CIPP Sewer Main Rehabilitation Projects. In *Proceedings of the NASTT's 2015 No-Dig Show*, March 15-19, Denver, Colorado, Paper MM-T4-03-1.

*Dedicated to my parents and wife*

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# Chapter 1: Introduction

## 1.1 Background

Most of North America's current underground infrastructure utilities were installed in the 1950s and 1960s during a period of rapid growth in the economies of Canada and the United States (Hashemi et al., 2011). Today, failures of these aging systems have become an everyday news item as they have exceeded their design lives and significantly deteriorated. It is the utmost responsibility of municipalities to renew and maintain these aging and deteriorating underground infrastructures at a level of service satisfactory enough to ensure the public's health and safeguard the environment from pollution. However, renewal of this aging underground infrastructure is a substantial challenge faced by municipalities. Traditional replacement or renewal methods use open cut excavation, which can be costly and disruptive to the surrounding environment, particularly in areas that are highly populated or have problematic ground and site conditions. The current alternatives to open cut excavation have evolved so that replacing or repairing old pipelines has fewer social and environmental impacts during the installation. As the crucial feature of these techniques is that they perform no actual excavation, they are known as Trenchless Technologies (TT) (Faghih, 2014). TT are a viable option due to the availability of various equipment, methods, and materials. Furthermore, advancements in TT fields have made them available for numerous applications, such as replacement, repair, rehabilitation, renovation, inspection, underground utility construction and leak detection (Faghih, 2014; Allouche et al., 2000; Najafi, 2010). However, due to ever increasing labor, energy, and machinery costs, replacing old, leaking pipes with new ones is becoming increasingly difficult and uneconomical (Delaney et al., 2007). For this reason, various methods of in-place repair or rehabilitation have been invented to avoid the expenses and hazards associated with digging up and replacing pipes or pipe sections, as well as to avoid significantly disturbing the public. One of the most successful pipeline repair or trenchless rehabilitation processes currently in use is cured-in-place pipe (CIPP).

Among the different trenchless pipe rehabilitation techniques, CIPP is considered a safer, more cost-effective, efficient, and productive alternative. A survey of the U.S. sanitary and storm sewer systems conducted by Hashemi and Najafi (2008) showed that of all the different technologies in the years 2007 and 2008, CIPP was the topmost used method in contrast to other TT methods such as pipe bursting, sliplining, point repair and horizontal directional drilling (HDD). This trenchless rehabilitation technology allows placing new pipe within the original pipe with stand-alone structural characteristics while eliminating infiltration and exfiltration through open joints, holes and fractures at a reduced cost, in less time, and with fewer inconveniences to the owners and surrounding community ("Lanzo Lining Services Inc.," 2010). The cured-in-place lining procedure involves inserting a resin-impregnated fabric tube into an existing damaged lateral through air inversion. The fabric used in these pipes is polyester felt or reinforced fiberglass. The inversion process is used to insert the liner, and steam or water is used to cure the pipe (Conway, 2008).

Although CIPP is considered one of the most prominent trenchless rehabilitation technologies, relining using CIPP is not a straightforward process and has a number of issues and challenges. While most of the CIPP installation projects were successful, literature reveals that quite a few projects faced problems and challenges during the process. For instance, cracks, severe internal corrosion, grease build-up, root intrusion, joint misalignment, separation and/or leakage, excessive pipe deflection, lateral connection leakage, and grade and alignment are some of the pipe defect problems that make the cleaning or pipe preparation phase a significant challenge, and this is the preliminary step for the CIPP process (Selvakumar and Tafuri, 2012; Murray, 2009). In the CIPP installation of combined sewer overflow (CSO) pipes by the Northeast Ohio Regional Sewer District (NEORSD), significant elevation differences caused the contractor to handle considerable issues, including hydrostatic pressure on the downstream terminus of the CIPP liner, difficulty controlling the advancement of the CIPP liner on the steep slopes, and on one occasion, the downstream end/backstop failed during the CIPP installation (Lucie et al., 2014). During liner installation, improper monitoring of the installation pressure may create construction hassles such as a higher installation pressure, which may in turn result in a denser but thinner product. On the other hand, low installation pressures may leave a less dense, thicker, but weaker liner (Davison and Coté, 2015). A recent installation in Carrboro, NC, observed that a combination of high temperature/humidity and unanticipated pull loads resulted in a slower pull, and the increased temperature/humidity combined with the extra time required to pull the liner in place led to it gelling before it was installed, resulting in a "C" shaped hardened liner stuck within the host pipe (Leitch et al., 2015). In a CIPP project in the province of Quebec, problems with matching the manufactured liner with the existing pipe was a common issue found (Alzraiee et al., 2014). Moreover, service undercut, folds, lift, peeling and wrinkles or bubbles in the liner are some examples of post-installation deficiencies that have been observed in different CIPP projects (Pennington et al., 2005; Davison and Coté, 2015; Wong et al., 2015; Deb et al., 1999). In addition, the use of styrene in the resin systems during the CIPP rehabilitation storm sewer pipes may cause fish kills in the water source downstream from the resins and effluent leaked or chemicals leached from the cured pipe after the installation is completed (Donaldson, 2009; Downey and Koo, 2015; Lee, 2008). This study outlines the issues and challenges associated with CIPP rehabilitation projects of sewer mains, water mains and service laterals. It provides a concise but comprehensive summary of all information needed by researchers and engineers to understand the obstacles and challenges that may arise during CIPP rehabilitation work, as well as relevant measures adopted in current practices to resolve these issues and benefit the trenchless CIPP industries.

According to the Federation of Canadian Municipalities (2012), the network of underground infrastructures in large Canadian cities are aging; municipal governments must now properly plan the maintenance and rehabilitation of their current deteriorating underground water and wastewater distribution systems with utmost urgency (Navab, 2014; Allouche and Freure, 2002). Productivity data plays a major role in effective planning, budget allocation, and establishing an efficient rehabilitation program. However, no study has analyzed the productivity of the CIPP rehabilitation process, while several studies have been conducted to assess the productivity of other trenchless techniques like HDD and pilot tube microtunnelling (PTMT) (Ali et al., 2007; Sarireh, 2011; Olson and Lueke, 2013). This thesis also focusses on productivity analysis of CIPP sewer main rehabilitation projects and derives the productivity factor for varying pipe diameter and liner thickness.

Furthermore, laterals comprise a significant portion of the wastewater distribution system, and deteriorated laterals can have a major impact on the performance of the sewer system and treatment plants. Cracked or broken laterals can allow groundwater and infiltrating rainwater (clean water) to enter into the sewer system which, at high levels, can result in higher demands at the treatment facility or overload the sewers and produce sanitary sewer overflows (SSOs) (Sterling et al., 2010). Repairing or replacing sewer mains to remove inflow and infiltration (I/I) may also be less effective than predicted until the laterals are fixed (Sterling et al., 2010; Simicevic and Sterling, 2006a). The City of Edmonton upholds over 300,000 sanitary, storm and combined sewer service laterals, with the outdated installations approaching 100 years in age. Each year, the City of Edmonton's Drainage Services Department receives an average of 6,000 calls related to service lateral problems (Kristel et al., 2009). To address this situation, a service connection relining program is considered one of the most effective strategies. Among the various types of CIP liner, main and lateral cured-in-place liner (MLCIPL) provides successful rehabilitation of both mainline and lateral. However, one of the challenges of a MLCIPL project's construction planning stage is selecting an appropriate construction set-up, such as crew and equipment conformation. Simulation is an excellent tool for project management as it has the capability to capture the uncertainties and risks of construction projects and develop alternative options for the stakeholders of the project in a very short period of time (Ruwanpura and Ariaratnam, 2007). Therefore, this research focuses on applying a special purpose simulation system on a MLCIPL lateral relining process to assist the decision makers in properly using resource composition and improving the productivity of the system.

## 1.2 Research Motivation

Among the different trenchless pipe rehabilitation techniques, CIPP is considered a safe, cost-effective, efficient and productive alternative. However, relining using CIPP is not a straightforward process and has a number of issues and challenges. Risks and/or deficiencies in a CIPP project may result in a direct economic loss to the industry. As a result, CIPP industries and municipalities are constantly concerned about probable issues in any relining project. However, the literature provides limited information on issues and complications encountered during CIPP rehabilitation processes. Therefore, a systematic review and comprehensive summary of the overall obstacles and risks faced in CIPP projects have been presented in this research.

A significant amount of a CIPP sewer main project is associated with large diameter pipes (greater than or equal to 375 mm), which are considered more challenging due to high flow, deeper access pits or manholes, potentially thicker calcite inside the pipe, etc. As a result, relining of large diameter sewer mains is not a straightforward process, and it is associated with a number of uncertainties that affect the productivity of a project. Although productivity is the most significant factor for the planning and budget allocation of CIPP projects, there is limited information on the topic in literature. For municipalities to establish an efficient asset management program, productivity data is crucial. Understanding the CIPP process and the effects of productivity factors on the varying pipe diameters and liner thicknesses can help the CIPP service providers plan their resources efficiently and run their projects more economically. To assist contractors and engineers in estimating CIPP project costs and schedules, this research describes the CIPP process and conducts a productivity analysis of more than 40 sewer mainlines in Edmonton, Alberta, rehabilitated through the CIPP inversion process.

One of the challenges of a project's construction planning stage is selecting an appropriate construction set-up, such as crew and equipment conformation. It is essential to choose a suitable method that can save cost, time, and avoid significant disruptions in the area, especially for projects in urban settings. Management must consider possible resource combinations (crew and equipment), test various construction scenarios, calculate the associated cost and time for each scenario, and determine the most desirable solution. In this research, a simulation-based approach was used to assist decision makers in choosing the best crew and equipment combination for a MLCIPL lateral relining process. In addition, this study suggests an amendment to the installation sequence to improve the construction productivity of MLCIPL projects.

## 1.3 Research Objectives and Scope

Considering the limitations in previous literature and research, three objectives have been set in this thesis.

***Objective 1:*** To present a systematic review and provide a comprehensive summary of problems and challenges in CIPP installation, as well as relevant measures adopted in current practices to resolve these issues.

***Objective 2:*** To investigate the CIPP process and conduct a productivity analysis on sewer main rehabilitation projects in Edmonton, Alberta, rehabilitated through the CIPP inversion process. This study illustrates how varying pipe diameters and liner thicknesses affect productivity of the CIPP lining process.

***Objective 3:*** To show the application of Simphony simulation on the MLCIPL lateral relining process and analyzing the productivity of these MLCIPL projects with respect to different crew and equipment combinations. Modifications in the installation sequence are also suggested to improve the productivity.

This systematic review and comprehensive summary may benefit trenchless CIPP companies and water distribution and wastewater municipality sectors in understanding challenges that can arise during CIPP installation work. The productivity analysis results of sewer main CIPP projects will contribute to more accurate estimation of CIPP project productivity, thereby helping with effective CIPP rehabilitation project planning and management. The simulation-based model can be applied to assist decision makers in choosing the best crew and equipment combination for MLCIPL lateral relining.

## 1.3 Research Methodology

This study was conducted in collaboration with the Consortium for Engineered Trenchless Technologies (CETT), a research group at the University of Alberta, and IVIS Inc., one of the largest CIPP service providers in Edmonton. This thesis is focused on the trenchless rehabilitation technique of underground infrastructures by CIPP and it is organized into three sections. In the first section, key issues and challenges encountered during CIPP installation projects of sewer mains, water mains and service laterals were systematically reviewed from academic publications, industrial guidelines, and specifications from various practitioners specializing in CIPP installation. Site visits to CIPP installation projects, performed in different municipalities by specialized CIPP industries, also provided a portion of the information. After that, a systematic review and summary of problems and challenges in CIPP installation, as well as relevant measures adopted in current practices to resolve these issues, was presented.

In the second section of this study, more than forty sewer pipeline rehabilitation projects in the City of Edmonton completed by IVIS Inc. were analyzed to perform a CIPP productivity analysis. The time and number of crew members required for different steps in the CIPP process have been tracked to determine productivity with respect to different pipe diameters and liner thicknesses.

The third section presents a special purpose simulation model developed by Simphony to predict the productivity of MLCIPL projects in comparison with different crew size and equipment combinations. As an input for the simulation model, time distributions were obtained from the installation site visits. Additionally, a modification in the MLCIPL installation sequence was suggested to improve the productivity.

## 1.4 Structure of the Thesis

The remainder of this thesis is organized into the following chapters:

*Chapter 1* provides a background on the CIPP rehabilitation process. The thesis objectives, research methodology and the thesis structure are discussed.

*Chapter 2* discusses the CIPP process and its historical and commercial background. This chapter also points out the importance and challenges of lateral rehabilitation and describes the MLCIPL lateral relining procedure. In addition, a brief review of the productivity and special purpose simulation is provided.

*Chapter 3* provides a systematic review on the challenges of CIPP installation. It describes key challenges and issues related to CIPP installation with respect to five different categories: (I) pipe condition and configuration, (II) pre-installation, (III) challenges during installation, (IV) post-installation, and (V) environmental challenges.

*Chapter 4* investigates the productivity analysis of sewer main CIPP rehabilitation projects and its influence on pipe diameter and liner thickness.

*Chapter 5* illustrates the application of special purpose simulation by Simphony on MLCIPL lateral relining processes. Furthermore, productivity analysis of MLCIPL projects in regards to different crew and equipment combinations and productivity enhancement by utilizing modified MLCIPL activity sequences have been discussed.

Finally, *Chapter 6* discusses research conclusions and highlights the results and findings of this thesis. It also proposes future research areas to further develop the potentials of this research in the CIPP field.

# Chapter 2: Literature Review

## 2.1 Introduction

This chapter provides a literature review on sewer mainlines rehabilitation, lateral rehabilitation, productivity, and special purpose simulation by Simphony. The sewer mainlines rehabilitation section examines the background of CIPP and the CIPP process. The lateral rehabilitation section examines system components of lateral distribution and the importance, challenges and available technologies of lateral rehabilitation. The productivity section comprises terminological definitions, calculation methods and parameters for the productivity study. Finally, the simulation section provides a literature review and background study of special purpose simulation by Simphony.

## 2.2 Sewer Mainlines Rehabilitation

From the literature, it is estimated that the United States contains approximately 16,000 publicly owned wastewater systems, comprising approximately 740,000 miles of gravity sewers, and 25% of the gravity sewer network is more than 40 years old (Selvakumar and Tafuri, 2012). Moreover, different problems in the sewer mainlines like cracks, internal corrosion, grease build-up, root intrusion, joint misalignment, and separation are responsible for sewage overflow and unwarranted infiltration. Therefore, the rehabilitation of aging and deteriorating sewer mainlines is currently a crucially pertinent topic for most water utilities. The rehabilitation of mainline sewers denotes a more extensive or purposeful effort to renew portions of a sewerage system. As illustrated in Figure 2-1, CIPP, close-fit linings, grout-in-place, spiral-wound linings, panel linings, spray-on/spin-cast linings, and chemical grouting are different rehabilitation methods applied to sewer mainlines (Sterling et al., 2010).

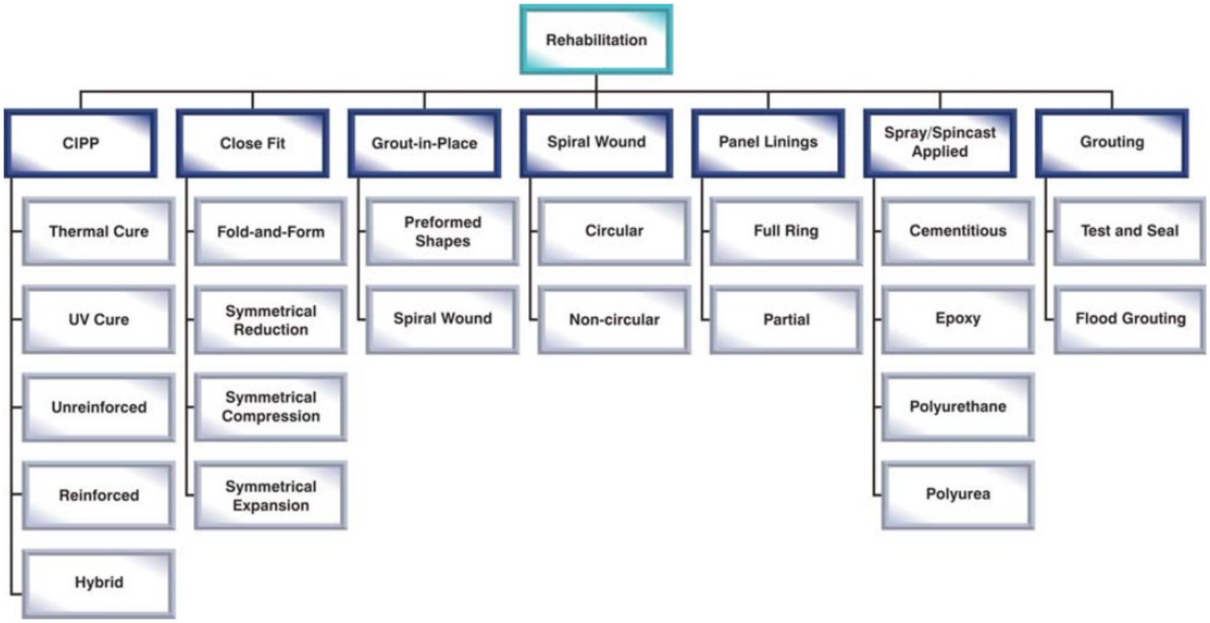


**Figure 2-1: Rehabilitation approaches for sewer mainlines (Sterling et al., 2010)**

CIPP is considered by far the most prominent method for rehabilitating sewer mainlines (Allouche et al., 2014). This trenchless rehabilitation technology allows placing new pipe within the original pipe with stand-alone structural characteristics while eliminating infiltration and exfiltration at a reduced cost, in less time, and with fewer inconveniences to the owners and surrounding community ("Lanzo Lining Services Inc.," 2010).

### 2.2.1 Historical and Commercial Background of CIPP

The first known municipal use of a CIPP lining took place in Hackney, East London, in 1971 when a 230-ft (70-m) length of the Marsh Lane Sewer was relined. The Marsh Lane Sewer is a 100-year-old brick, egg-shaped sewer with dimensions of 3.85 ft × 2 ft (1.175 m × .610 m). After successful installation of this project, the inventor Eric Wood, with entrepreneurship support from Doug Chick and Brian Chandler, registered the company Insituform Pipes and Structures, Ltd., and proceeded to market the technology and make improvements in its materials, preparation, and application (Allouche et al., 2014; Downey, 2010). Eric Wood applied for the first patent on the CIPP process on August 21, 1970, in the U.K. and was granted his first U.S. patent named "Method of lining a pipe" (U.S. Patent No. 4009063) on February 22, 1977 (Allouche et al., 2014; Wood, 1977). Through advancements in the process and the integration of modern technologies, CIPP received more attention from utility contractors and municipalities. Over time, other CIPP companies entered the market with similar and competitive technologies (Allouche et al., 2014).

In the United States, the first CIPP liner was installed by Insituform in 1976 on a 12-inch diameter line in Fresno, California. Since then, approximately 19,000 miles (100 million ft) of CIPP liner have been installed by U.S.-based Insituform contractors. Additionally, one assessment states that all-inclusively, approximately 40,000 miles (210 million ft) of CIPP liners have been installed since 1971 (Allouche et al., 2014).

### 2.2.2 CIPP Process

Repair of underground facilities by excavation and installation of new pipe to replace the old one is becoming progressively challenging and uneconomical due to ever increasing labour, energy, and machinery costs. To avoid the expenses and hazards associated with digging up and replacing pipes or pipe sections, as well as to avoid significantly disturbing the public, different methods of in-place repair or rehabilitation have been invented. Among the rehabilitation methods currently being used, CIPP is considered one of the most successful pipeline repairs or trenchless rehabilitation processes (Delaney et al., 2007). According to ASTM F1216, CIPP is defined as a technique to reconstruct pipelines and conduits by the installation of a resin-impregnated, flexible tube, which is inverted into the existing conduit by utilizing a hydrostatic head or air pressure. The resin is cured by circulating hot water or providing controlled steam within the tube, and after curing, the finished pipe will be continuous and tight-fitting (ASTM, 2007). Cured-in-place pipe has achieved wide recognition and approval because of its versatile application on pipeline rehabilitation. The key features of CIPP are as follows ("Lanzo Lining Services Inc.," 2010):

- CIPP is able to span a diameter range of 4 inches to over 120 inches (Sterling et al., 2010).
- CIPP has been used to rehabilitate sections of pipe over 3,000 feet in length ("Lanzo Lining Services Inc.," 2010).
- CIPP can rehabilitate non-circular pipe configurations such as ovals, boxes, bends and transitional diameters without digging.
- CIPP is used to rehabilitate partially as well as fully deteriorated pipe.

- CIPP is used for gravity, internal pressure and vacuum applications.
- CIPP is used in extremes of both temperature and pH.
- CIPP eliminates inflow and infiltration, as well as exfiltration.
- CIPP's smooth inner surface increases the flow capacity of the existing pipe.
- CIPP has ASTM F1216 and ASTM F1743 installation specifications, and CIPP tube and resin materials are specified by ASTM D5813.

Pipe preparation, wetout, and relining are the three significant phases of the CIPP process. In the initial step of the preparation process, existing pipe is CCTV-inspected for debris, roots, damage, offset joints, or any other incongruity that may impede proper CIPP installation. Inspection also requires measuring the pipe diameter, pipe length, manhole depths and groundwater depth, as well as recording pipe location and other important conditions (e.g. soil type, overhead power lines, railway, backyard easement, excessive sewerage flows, etc.) for planning purposes. Pipe preparation may involve internal mechanical cleaning and grinding to remove roots, protruding laterals, encrustations, or other impediments in the pipe. Collapsed pipe or severely offset joints (i.e. 40% of the diameter) typically require point excavations at those locations, while loose dirt, debris, or tuberculation may involve high pressure water or mechanical cleaning with a final pre-lining inspection of the pipe's entire circumference ("Lanzo Lining Services Inc.," 2010). The structural requirements of the liner are designed according to the procedures specified in ASTM F1216 (Sterling et al., 2010). In general, liner thickness calculation through the application of the ASTM F1216 equations results in a conservative design (Allouche et al., 2014; Zhao et al., 2005). However, such conservatism from design may provide some leeway to adjust liner flaws like locally weak or porous areas of the liner that are not detected by the quality assurance (QA) or quality control (QC) procedures (Allouche et al., 2014).

After proper pipe preparation and liner thickness design, the CIPP tube is prepared. In the earliest CIPP installations, the CIPP tube was made of a needled polyester felt and served only as a carrier for the resin that was the central provider to the mechanical properties of the system. During the 1990s, the U.S. marketplace saw an influx of other forms of tube construction, such as the insertion of reinforcing materials like fiberglass, aramid fibers or carbon fibers in some configuration(Allouche et al., 2014). The reinforcement may be placed at selected points within the thickness of the tube wall, or the wall may be made primarily of braided reinforcing layer(s)

(Allouche et al., 2014; Rahaim, 2009). Reinforced tube construction allows designing a thinner CIPP liner, which leads to a more complex mechanical performance of the liner. As well, the decreased thicknesses are more vulnerable to the effects of host pipe and liner imperfections on the structural analysis. However, the strength of a CIPP liner can be improved by using fiber-reinforced liners and woven liners (Sterling et al., 2010). Akinci et al. (2010) presents the reviews of new composite tube materials.

After a tube of proper diameter and thickness has been matched to the original host pipe, the CIPP process moves forward with resin-impregnation, which is also known as wetout process. Polyester, vinyl ester, and epoxy resins are three main types of thermoset resins that are compatible for use in CIPP rehabilitation projects (Allouche et al., 2014; Rose and Jin 2006). Among them, the isophthalic polyester resins are most commonly used and employed in more than 80% of the global CIPP market (Allouche et al., 2014). Due to lower costs and an adequate levels of water and chemical resistance, polyester resins are preferable over vinyl ester and epoxy resins for most municipal sewer applications. Nevertheless, vinyl ester resins offer improved initial and retained structural properties than the standard polyester CIPP resins, and they are normally used in CIPP applications where superior chemical and temperature resistance is mandatory (Allouche et al., 2014). Epoxy resins are mostly used in pressure pipe and potable water applications; they can also be utilized in places with stringent rules banning the release of styrene odors. The research of Kleweno (1994), Hayden (2004) and Moore (2012) provide the properties of resins used for CIPP applications.

During the impregnation of the selected resin system into the CIPP tube, air must first be evacuated to create conditions for vacuum impregnation. The catalyzed resin is then introduced into the tube under vacuum conditions so that air is completely displaced with resin while the resin saturates the fabric. The tube is then put through a pinch roller set to an appropriate thickness so that a standard amount of resin is introduced into the tube (Figure 2-2). The volume of resin should be sufficient enough to fill all voids in the tube material at nominal thickness and diameter. According to ASTM F1216, the volume should be adjusted by adding 5–10% excess resin to account for the change in resin volume due to polymerization and to accommodate for any migration of resin into the cracks and joints of the host pipe (ASTM, 2007). Finally, the tube is loaded into a refrigerated truck for transportation to the jobsite. After wetout and during transportation to the site, resin-saturated liners are kept in refrigerated condition to keep away from premature curing of the liner ("Lanzo Lining Services Inc.," 2010). In the case of man-entry pipes, the wetout process may take place at the construction site because for large diameter liners, the higher liner thickness with respect to the large host pipe diameter means that the lay-flat liner becomes too weighty or too wide to transport when wetout. However, onsite resin impregnation results in an additional burden on quality control for the wetout process (Allouche et al., 2014).

**Figure 2-2: Wetout (Photograph taken at IVIS Inc.)**

After accomplishing the wetout process, the resin-saturated liner tube is installed into the host pipe to be relined. Liner installation can be done in two ways: the first way is pulling the liner into place and then inflating it to a close fit using water or air. The second way is liner inversion along the host pipe by utilizing water or air pressure (Figure 2-3). From the earliest time of CIPP installation until 1973, all CIPP liner installations were accomplished by the pull-in-and-inflate procedure. After the introduction of coated felt in 1973, the liner inversion process became a more appropriate method (Allouche et al., 2014). In the liner inversion process, the uncooked resin-saturated liner is forced by water or air pressure to turn itself inside out along the host pipe section to be relined.

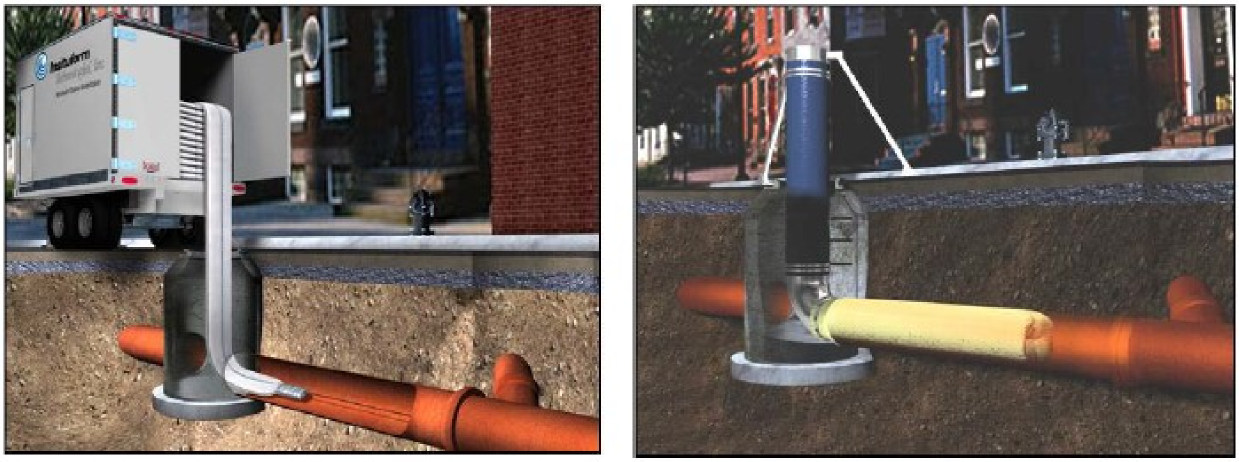


**Figure 2-3: CIPP installation options: liner pull-in (left) and liner inversion (right) (Allouche et al., 2014)**

Once the uncooked liner is in place and held tightly against the host pipe, the liner can be cured using hot water, steam or ultraviolet (UV) light that triggers the liner resin to become a cross-linked and solid liner material. In 1986 in Europe, iNPIPE developed and used UV light-cured liners, which are typically used for a seamless, spirally wound, glass-fiber tube impregnated with polyester or vinylester resins (Allouche et al., 2014). The key drawback associated with water inversion and curing is the quantity and availability of the inversion water. This shortcoming may be resolved with using air instead of water to create the inverting force. Although water is necessary to produce steam, the quantity of water in the form of steam is only 5–10% of that required for water inversion, cure, and cool down (Delaney et al., 2007). As a result, curing process by introducing steam is mostly used for CIPP applications at the present time. To ensure proper curing of full thickness of the liner is essential so that thermal or other stresses are not introduced into the liner in a partially cured state.

Once installed, cured, and cooled, the CIPP is fully opened on both ends while any lateral connections leading to the pipe are reinstated with remotely operated cutting machines (Figure 2-4), followed by a final CCTV inspection and sample collection. In the case of pipe diameter less than 300 mm, generally round-shaped samples are collected from the jobsite by using a cylindrical mold in the downstream manhole section. For larger pipes, however, the sample is prepared in the shop and plate shape sample is collected for testing (Navab, R., personal communication, October 15, 2014).

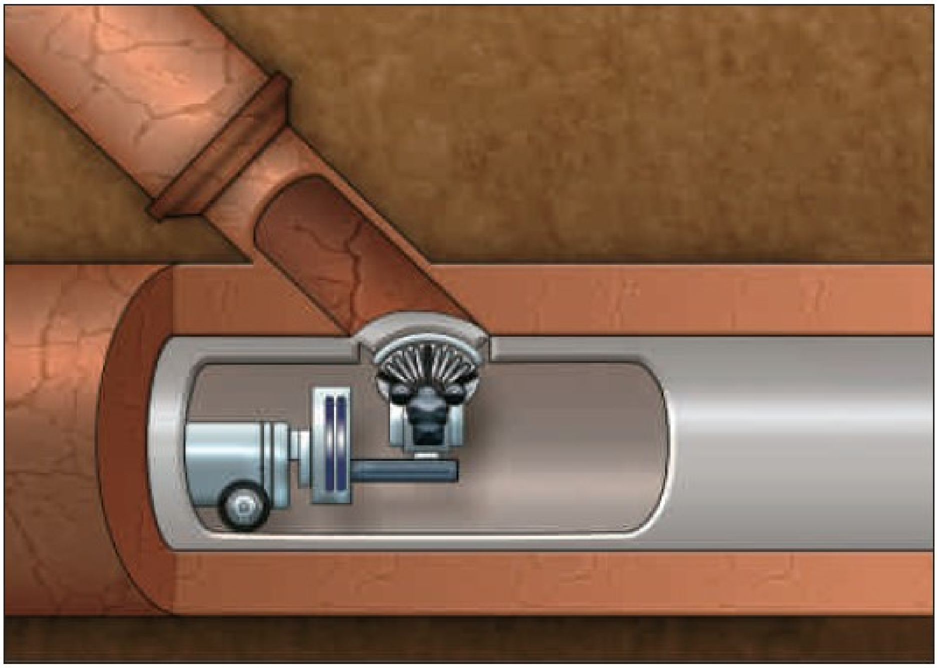


**Figure 2-4: Robotic reinstatement of house connection or “lateral” sewer (“Lanzo Lining Services Inc.,” 2010)**

The original CIPP product was a needled felt tube, impregnated with polyester resin that was inverted into a sewer through a manhole by pulled-in and-inflate method and cured using hot water. This product is still used for gravity sewers, but by this time, CIPP has become a versatile method with innovative materials and technologies. The main differences in CIPP technologies available today are based on tube construction, method of installation, curing method, and type of resin, all of which are featured in Figure 2-5 (Sterling et al., 2010).

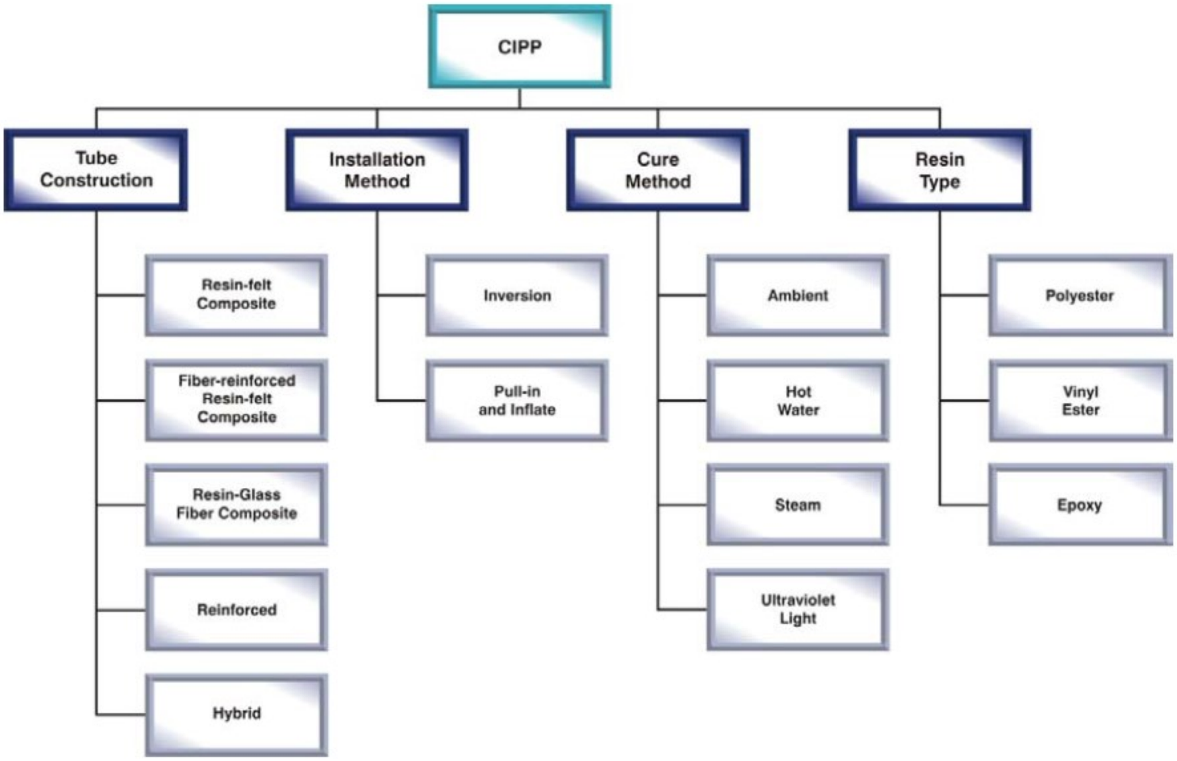


**Figure 2-5: Summary of common CIPP technologies (Sterling et al., 2010)**

## 2.3 Lateral Rehabilitation

Sewer lateral is defined as the segment of pipe, appurtenances and fixtures that connect a building sewer to the city sewer main (City of La Mesa). Currently available literature indicates that the service laterals are among the leading contributors of inflow and infiltration (I/I) and root intrusion in sewer systems (Goodman et al., 2009), but there have still been slight developments in the improvement of lateral rehabilitation. Various strategies, technologies and products were considered and evaluated by numerous municipalities and private companies to abolish I/I, SSO reduction, and root intervention problems. On account of a variety of legal issues and dearth of funding, only in recent years municipalities have begun addressing the problems with service lateral connections, which are considered the last frontier in the battle to reduce I/I and SSOs. To achieve a leak- and root-free structure, restoration and/or repair of sewer laterals is essential.

### 2.3.1 Importance of Lateral Rehabilitation for Sustainable Wastewater Distribution Systems

Lateral rehabilitation is of utmost importance to protect public health, safety, and the environment as reducing the number and severity of sewer backups and overflows will minimize inconveniences to residents and businesses. Another significant purpose of lateral rehabilitation is improving sewer system performance by reducing I/I of storm water into the wastewater collection system. I/I and root intrusions are responsible for the majority of avoidable expenses in sanitary sewer systems. I/I and roots often surcharge systems and cause raw sewage to back up into homes and businesses. It can also cause sewage to overflow the system and create unhealthy situations, frequently spilling sewage into oceans, lakes, rivers and streams, thus killing fish and other life forms and destroying their habitat for years (City of Santa Monica). Most infiltration enters sanitary sewer systems at five critical points: pipe joints, pipe cracks and missing sections, maintenance holes, service line connections, and service laterals.

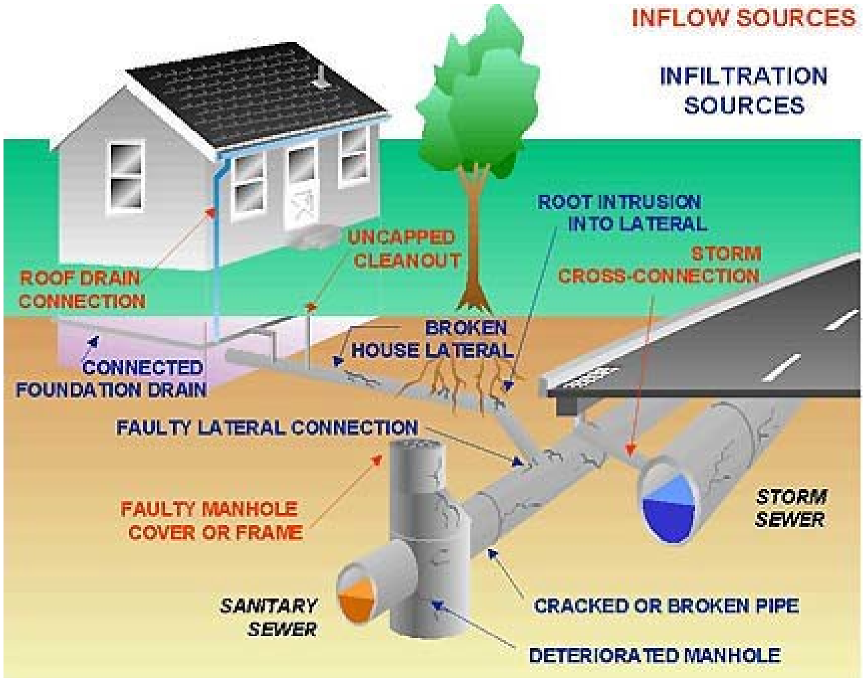


**Figure 2-6: Infiltration and inflow sources in a sewer network system (City of Santa Monica)**

Figure 2-6 shows all sources of I/I in a sewer network system (City of Santa Monica). The WERF survey of 2004 revealed that private sewer laterals contributed about 7–80% of the total I/I to the wastewater system with the mean and median estimation at 40% (Simicevic and Sterling, 2006b). Literature reveals that sewer rehabilitation alone is not effective for I/I reduction. The Oak Valley neighborhood of Nashville, TN, is one example where a regression analysis was used to compare I/I reduction from pre-mainline rehabilitation, post-mainline rehabilitation, and post-lateral rehabilitation. Results suggested that only mainline rehabilitation results in a 52% reduction in peak hourly flow, whereas combined lateral and mainline rehabilitation resulted in an 84% improved reduction of pre-rehabilitation flow (Simicevic and Sterling, 2006a). Therefore, to ensure a successful wastewater collection system and overflow elimination strategy, both sewer mainline and lateral rehabilitation should receive scrutiny.

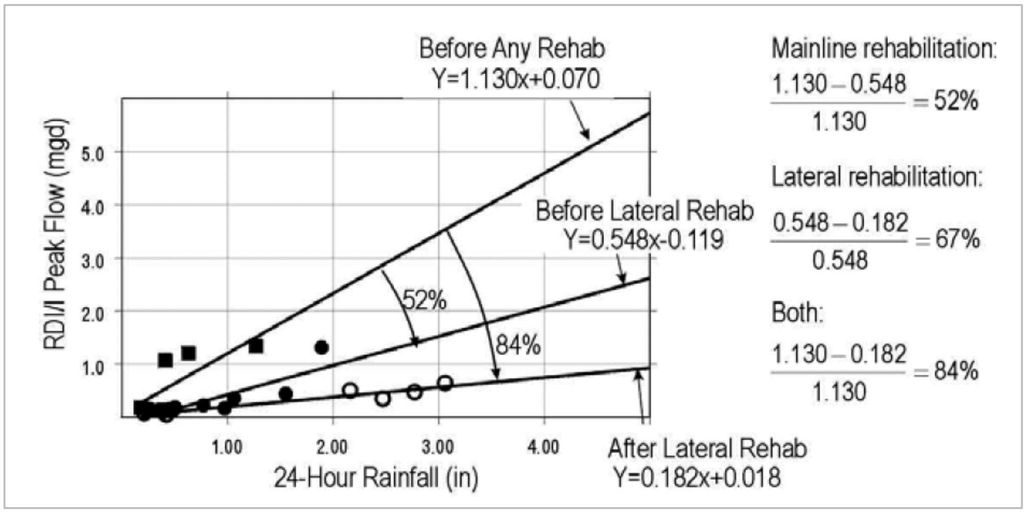


**Figure 2-7: Comparison of peak hourly flow reduction in Oak Valley after mainline and lateral rehabilitation (Simicevic and Sterling, 2006a)**

### 2.3.2 System Components

Each mile of mainline in the U.S. has 30 to 300 laterals (on average 75–85 per mile), and each lateral is an average length of 50 feet (WERF survey), meaning there are over 76 million sewer laterals in the U.S. alone (U.S. Census Bureau). From the EPA report, it is obvious that most private sewer laterals are vitrified clay pipe (VCP) (51.8 %) and PVC pipe (26.6%) (Figure 2-8). The category “other” in the figure refers to Orangeburg pipes and asbestos-cement pipes, which are no longer installed. In terms of pipe size for laterals, they also reported that most of the private sewer laterals in their systems were 4-inch pipes (62.6%) and 6-inch pipes (29.7%). Smaller diameters (3 inches or less) and larger diameters (up to 12 inches) were reported in smaller quantities (Figure 2-8) (Sterling et al., 2010).

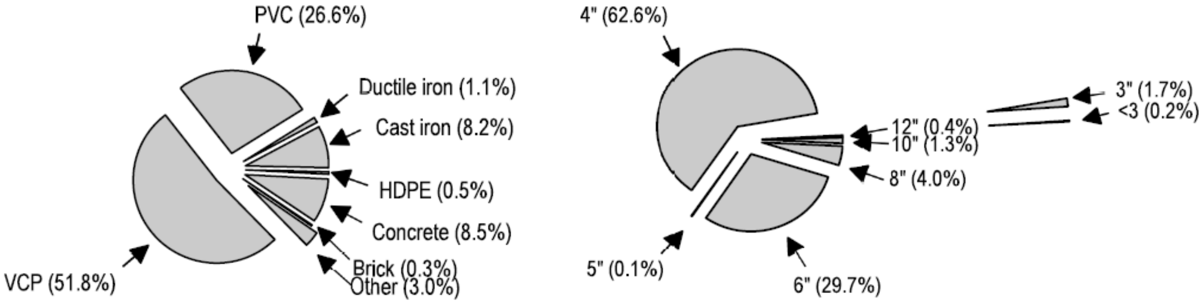


**Figure 2-8: Pipe types (left) and sizes (right) used for sewer laterals (Sterling et al., 2010)**

### 2.3.3 Challenges

Although they are just additional pipe segments connected from building properties to the mainline sewers, sewer laterals have several physical and administrative conditions that make both assessment and restoration programs more challenging for them than for the mainline sewers (Sterling et al., 2010). Figure 2-9 represents a general sketch of a sewer lateral connecting to a mainline in a street, in conjunction with some of the typical conditions and illegal drain connections (such as roof drains) that result in high I/I from laterals.

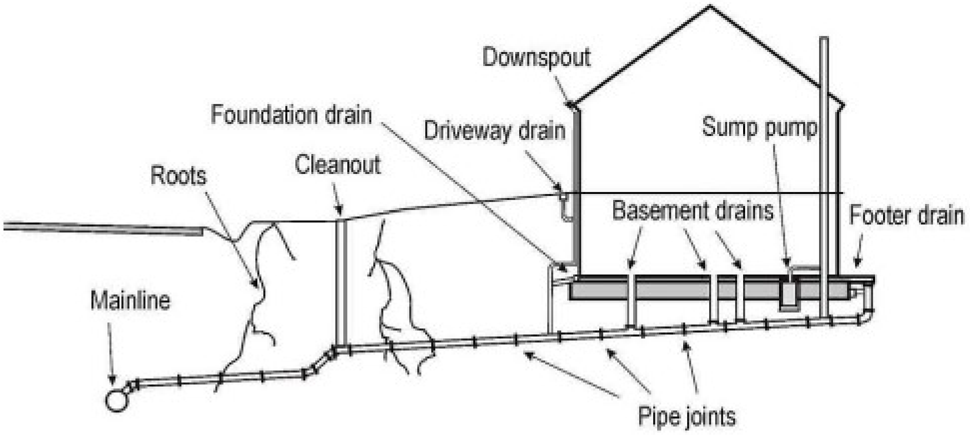


**Figure 2-9: Typical layout of sewer laterals (Simicevic and Sterling, 2006b)**

Some of the distinctive physical characteristics of laterals that have an effect on pipe inspection or rehabilitation activities compared to sewer mainlines are as follows (Sterling et al., 2010):

- Lateral pipes are mostly of small diameters (4 or 6 inches).
- They transition in diameter at the foundation or property line (for example, from 4 to 6 inches).

- Sharp bends and multiple fittings are common (at cleanout location).
- Inspection of laterals is a challenging task.
- Lateral pipes have no access points other than through the mainline connection or a cleanout, and sometimes from inside of the house.
- Different types of lateral to main pipe connections (Tee, Wye and Double Tee Stack) make the rehabilitation process for laterals very complex.

Moreover, there are legal and financial issues that make lateral rehabilitation more challenging. Because of the abundant number of service laterals and the associated costs, lateral rehabilitation represents a significant expense. The problem is further compounded because of the legal jurisdiction and private ownership issues, and ownership of sewer laterals varies significantly for municipalities even within a single metropolitan area (Sterling et al., 2010). Therefore, municipalities are often unwilling to resolve I/I problems from laterals by rehabilitation (Tafuri and Selvakumar, 2002).

### 2.3.4 Available Technologies

Commonly available methods for the rehabilitation of lateral pipelines are CIPP relining, pipe bursting, chemical grouting, flood grouting, robotic repair, root control, and sliplining.

In the pipe bursting process, a cone-shaped bursting head is used to split the existing lateral pipe, the fragmented pieces are pushed aside, while a new pipe of identical or larger diameter is simultaneously pulled behind the bursting head along the old pipe alignment (Allouche and Ariaratnam, 2002; Islam et al., 2012). Two pits (entry and exit pit) are compulsory during the setup for each lateral replacement by pipe bursting, and the length of lateral bursting is generally 20–200 feet (Simicevic and Sterling, 2006b). Typically, pipe bursting is used for severely ravaged pipes or for pipes with unsatisfactory hydraulic capacity (since the existing pipe can be upsized by one size during replacement). It results in a permanent structural repair and is practical and fast, involving as little as a few hours to replace a single lateral. However, shortcomings of pipe bursting are that digging is required for pits, it is not appropriate for laterals with many bends, and it is uneconomic for very short laterals. In addition, there is a probability of surface heaving and damage to nearby utilities, foundations and pavement (Allouche and Ariaratnam, 2002).

Chemical grouting is considered a low-priced and speedy technique that is performed with a packer to isolate repairs where it is needed (Islam et al., 2012). Chemical grouting of sewer laterals is mostly implemented from the mainline; the first several feet into the lateral are grouted in order to make the lateral to mainline connection leak-proof. However, chemical grouting can also be executed through cleanouts where the entire length of lateral is grouted in 3–5 feet long increments. This technique does not provide structural repair; therefore, it is only ideal for structurally sound pipes. Furthermore, the durability of repair can be rather short in some ground conditions (up to 5 years). As a result, chemical grouting is normally used to eliminate infiltration, and it is carried out as a test-and-seal procedure.

In flood grouting technique, the mainline and lateral are surcharged with silicate-based grout to seal the cracks and broken parts and thereby remove infiltration. Alternatively, robotic repair sends a robot inside the lateral to inject remediable resin to the flawed soil-pipe region (Islam et al., 2012). Root control technique for the lateral pipelines could be either mechanical cutting or a chemical approach where the prevailing roots are destroyed through applying herbicides (Islam et al., 2012; Sterling et al., 2006). Sliplining technique is a process to insert a new pipe into the host pipe with or without bypass filling the annular space with cementitious grout (Islam et al., 2012).

#### *2.3.4.1 Cured-In-Place (CIP) Lining*

The cured-in-place lining procedure involves inserting a resin-impregnated fabric tube (polyester felt or fiberglass-reinforced material) into an existing deteriorated lateral through air inversion. The inversion process is utilized to insert the liner, and steam or ambient air is then introduced to achieve the curing of the pipe (Conway, 2008). For CIP lining, there are a variety of systems on the market that differ in the types of fabric and resins and the type of curing system. CIP lining can provide structural repair with negligible digging and minimum diameter reduction (Sterling et al., 2010). Simicevic and Sterling showed various types of CIP lateral liner (Figure 2-10), depending on the treatment of the lateral-mainline connection and the length of coverage of the lateral liner (Simicevic and Sterling, 2006b).

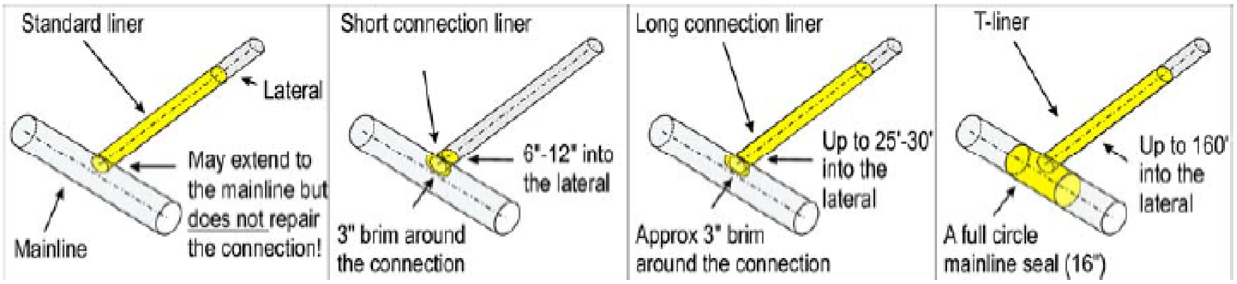


**Figure 2-10: Different types of CIP lateral liner (Simicevic and Sterling, 2006b)**

Among the different types of CIP lateral liners, the standard liner approach does not provide a proper seal for the lateral/mainline connection. The standard liner is shaped like simple tubes and can be installed through cleanout or small pits. As the lateral/mainline connection is the most critical point at a sewer lateral's deepest location, various systems have been introduced to offer a seal for only the connection or seals of the connection, and a short section of lateral (Sterling et al., 2010). Short connection liners are similar to this system with a flange inside the mainline and a smaller section of liner extending into the lateral and are often referred to as a "top hat". They are installed from the mainline and only address the leaked mainline-to-lateral connection, where a brim approximately 3 inches wide is created in the mainline around the connection and the connection extends a short distance (typically about 6 inches) into the lateral. Long connection liners, on the other hand, are inverted remotely from the mainline (usually up to 25–30 feet into the lateral) and create a brim similar to short connection liners around the lateral connection in the mainline (Simicevic and Sterling, 2006b). Recently, these systems have been conjoined into a system (T-liner) that consists of a full circle liner (typically 12 to 16 inches) inside the main line and a full CIP lateral liner with extent of coverage up to 160 feet (50 meters) into the lateral from the mainline connection (Sterling et al., 2010). In ASTM F2561, the T-Liner is denoted as the main and lateral cured-in-place liner (MLCIPL) (ASTM, 2011). In the lining process by MLCIPL, the lateral pipe is rehabilitated remotely from the main pipe and a lateral cleanout. The pipe renovation is achieved by inverting and inflating a resin-impregnated, single-piece lateral and main connection liner assembly (Figure 2-11).

**Figure 2-11: Resin-impregnated, single-piece lateral and main connection liner assembly prior to installation (site visit at an installation in Edmonton, Alberta)**

The liner assembly is pressed against the lined main pipe by inflating a bladder and held under pressure until the thermo-set resin has cured. When cured, the liner extends over a predetermined length of the service lateral and the full circumference of the main pipe connection, forming a continuous, single-piece, tight-fitting, corrosion-resistant and verifiable non-leaking cured-in-place pipe (CIPP) inclusive with gasket seals (Kiest and Gage, 2009). The materials and installation practices should follow the minimum requirements of ASTM F2561-11 (ASTM, 2011).

## 2.4 Productivity Considerations

Productivity is computed through the ratio of produced output to unit of resource input, such as labour, energy, raw materials, etc. (Equation 1). With respect to used resources, typical productivity ratios are: (a) the total factor productivity or multi-factor productivity, in which the output is in relation to all used resources; and (b) labour productivity, in which the output is in relation to simply labour (Vasely, 2015). Equation 2 is used to determine the labour productivity, where labour input is denoted by the employed persons, working hours or labour cost (Vasely, 2015; O'Grady, 2014). Temperature, wind speed, relative humidity, precipitation, type of work and crew composition are some factors that impact labour productivity (Khan, 2010). To assess the proficiency of a method, labour productivity is commonly calculated over time, which assists management in improving performance and saving costs (Vasely, 2015; Su, 2010).

$$\boldsymbol{Productivity} = \frac{\boldsymbol{Output}}{\boldsymbol{Resources\ used}} \text{ ..........................................................................} (1)$$

$$\boldsymbol{Labour\ Productivity} = \frac{\boldsymbol{Output}}{\boldsymbol{Labour\ Input}} \text{..........................................................................} (2)$$

In the construction industry, the amount of time required for accomplishing a unit of output is considered the resource input. Output unit is selected with the purpose of conducting productivity research. Productivity can be utilized to find a way to develop work output or quality without adding cost, time and resources (Navab, 2014; Kien, 2012). Conventionally, productivity is measured in two ways: (a) by the labor or crew performance required to finish a job unit, or (b) by the amount of job completed by a labor or crew in a given time and place (Dozzi and AbouRizk, 1993). For the CIPP process, productivity can be measured in two units: (a) man-hours to complete one foot of mainline (mhr/ft), or (b) the length (ft) of mainline completed by one man-hour (ft/mhr). For effective productivity investigation, the work parameters such as workers' proficiency levels, weather conditions, and equipment used in a productivity study must be well defined (Navab, 2014).

However, operating procedure and work sequence followed to reach the output are also essential considerations. Generally, each task consists of two types of works: (a) the basic productive work, which refers to the minimum amount of work that adds value to the product or service requested by the client; and (b) excess non-productive work, which is outlined as the physical or mental activities that could be necessary, but do not add any value to the end product or service (such as logistic operations, paperwork activities, maintenance, and traveling) (Navab, 2014; Carreira, 2005). Poor design of the procedure, utilizing inefficient methods and human errors due to insufficient training are some examples of non-value-adding tasks (Drewin, 1982). For productivity improvement, it is essential to minimize the non-productive activities from the whole working methodology (Navab, 2014).

Construction productivity plays a significant role in the project success, and high productivity leads to lower unit costs per task or operation. Regularly observing productivity allows decision makers to implement crucial changes to boost the project during unexpected events (Vaseli, 2015; Su, 2010). It must be mentioned that it is fundamental to present results validation and work conditions connected with the productivity data calculation (Vaseli, 2015).

## 2.5 Special Purpose Simulation (SPS) by Simphony

Simphony is a Microsoft Windows-based construction simulation tool to model discrete event simulation systems, originally developed under the guidance of the Natural Sciences and Engineering Research Council (NSERC) and the Alberta Construction Industry Research Chair Program in Construction Engineering and Management (Vaseli, 2015; Hajjar and AbouRizk, 2000). Simphony is regarded as an appropriate tool for integrating simulation into a construction management procedure (AbouRizk et al., 1999; Lueke et al., 1999). Utility construction projects applying trenchless techniques are excellent candidates for the application of computer simulation (AbouRizk et al., 1999; Ruwanpura and Ariaratnam, 2007).

In this research, simulation models were developed in Simphony.NET 4.0, which is the latest version of Simphony. Simphony offers a background for developing General Purpose Simulation (GPS) and Special Purpose Simulation (SPS) templates (Moghani et al., 2011). A SPS template is a collection of modelling elements designed to have a behavior customizable to a specific process; these elements usually have icons that resemble the real-world systems they represent. On the other hand, a GPS template is a collection of high-level elements that do not necessarily resemble a real-world system. Abstract elements such as activities, queues, and resources are utilized to develop models through a GPS template. Conversely, SPS templates consist of a set of elements related to a particular construction domain, which makes simulation more comprehensible for the industry (Moghani et al., 2011). Simphony provides a graphical user interface and hierarchical modeling capability, and its object-oriented application framework offers a structured approach to conveniently build any simulation template (AbouRizk et al., 1999). Based on the logic of a given process, users can drag and drop elements into the Simphony modeling interface, connect them and assign resources for diverse activities in the process. For every resource, statistical results are available in the process after the simulation runs (Moghani et al., 2011).

If needed, Simphony has features of Monte Carlo simulation purposes, and a simulation model can have any number of runs. Running a model for different scenarios and comparing them simultaneously is possible with Simphony as more than one scenario can be modeled in one simulation file. In addition, Simphony comprises statistical outputs and different kinds of reports, such as cost and resource utilization, which are helpful for construction management (Moghani et al., 2011).

# Chapter 3: A Systematic Review on the Challenges of CIPP Installations

## 3.1 Introduction

A large portion of current North American underground infrastructure was installed in the 1950s and 1960s during a period of rapid economic growth in Canada and the United States. Today, these aging systems have exceeded their design lives and have deteriorated to the point that failures are commonplace (Hashemi et al., 2011). Renewal of this aging and deteriorating underground infrastructure is a major obstacle faced by municipalities. Open-cut excavation methods are utilized for traditional replacement or renewal that can be costly and disruptive to the surrounding environment, particularly in highly populated areas and problematic ground and site conditions. In opposition, trenchless rehabilitation technologies employ innovative methods, materials and equipment that require minimum surface excavation and access. Among the different trenchless pipe rehabilitation techniques, cured-in-place pipe (CIPP) is considered a safe, cost-effective, efficient and productive alternative. However, relining using CIPP is not a straightforward process and has a number of issues and challenges.

Risks and/or deficiencies in a CIPP project may result in a direct economic loss to the industry. For instance, deficiencies like uncured linings must be fixed using spot repair, causing a significant cost impact. As a result, CIPP industries and municipalities are constantly concerned about probable issues in any relining project. Sterling briefly summarized the challenges for new trenchless installation techniques, such as inspection, location, condition assessment and asset management methods, as well as the challenges for renewal, including repair, rehabilitation and replacement technologies (Sterling, 2010). Later, Selvakumar and Tafuri discussed the separate issues for water and wastewater systems and showed the major issues and key challenges faced in terms of accelerating rehabilitation efforts in the most commonly used current technologies (Selvakumar and Tafuri, 2012). In addition, Selvakumar et al. provided a review of quality assurance and quality control (QA/QC) practices and summarized information on the installation and QA/QC practices for the trenchless rehabilitation of sewer and water transmission mains (Selvakumar et al., 2012). However, the literature provides limited information on issues and complications encountered during CIPP rehabilitation processes. This research provides a systematic review of the obstacles and risks faced in CIPP projects and those challenges were organized into five different categories with respect to various underground infrastructure systems (sewer main, water main and service lateral). Finally, concluding remarks are provided based on the findings and suggestions for future research on this topic.

## 3.2 Objective and Methodology

This research presents key issues and challenges encountered during CIPP installation projects of sewer mains, water mains and service laterals. The objective of this study is to present a systematic review and provide a summary of problems and challenges in CIPP installation, as well as relevant measures adopted in current practices to resolve these issues. A systematic review is generally not similar to a conventional literature review (Cooper and Hedges, 1994). According to Khan et al. (2003), "a review earns the adjective *systematic* if it is based on a clearly formulated question, identifies relevant studies, appraises their quality and summarizes the evidence by use of explicit methodology."

Initial steps to conduct a systematic review are framing the questions and identifying relevant works. Different risks and issues that may be encountered during CIPP rehabilitation process have been set as the systematic review question in this study. Information used in this research was collected from academic publications, industrial guidelines, and specifications from various practitioners specializing in CIPP installation. Site visits to CIPP installation projects, performed in different municipalities by specialized CIPP industries, also provided a portion of the information. The approach taken (academic review, industry information and site visits) is intended to provide a comprehensive overview of the topic.

## 3.3 Categories of Issues and Challenges

After an extensive systematic review, key challenges and issues related to CIPP installation have been recorded in a spreadsheet and classified into five different categories: (I) pipe condition and configuration, (II) pre-installation, (III) challenges during installation, (IV) post-installation, and (V) environmental challenges. These issues are discussed in the following sections.

### 3.3.1 Pipe Condition and Configuration

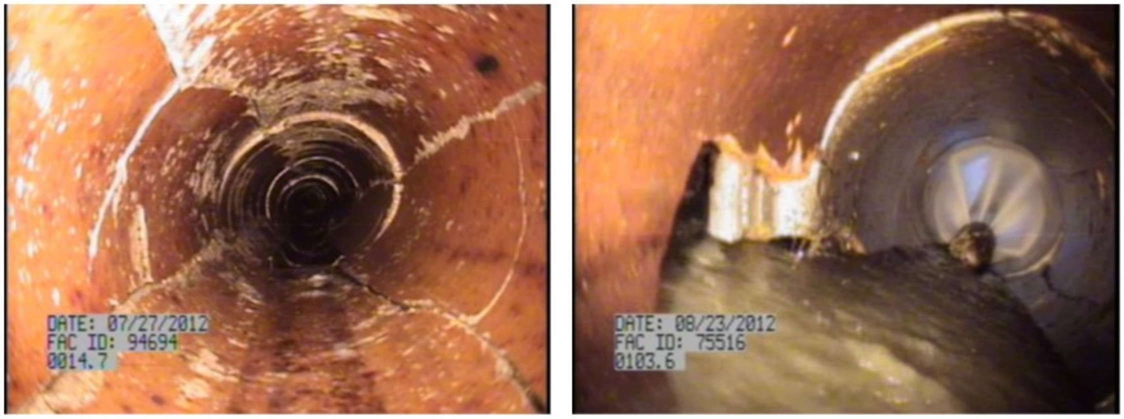
Pipe condition and configuration may present challenges during the initial stage of CIPP projects (pipe preparation or cleaning). The following subsections introduce pipe condition and configuration issues for different water distribution and wastewater collection systems.

#### *3.3.1.1 Sewer Main*

It is estimated that 25% of the gravity sewer network is more than 40 years old, whereas only 2% of the force main network is over 50 years old and 68% is less than 25 years old (Selvakumar and Tafuri, 2012). For sewer infrastructures, challenges can typically be related with cracks, severe internal corrosion (especially for concrete sewers), root intrusion, grease build-up together with gravel and debris, joint misalignment, excessive pipe deflection, separation and/or leakage, lateral connection leakage, and grade and alignment (Selvakumar and Tafuri, 2012; Murray, 2009). Pipe preparation or cleaning is the preliminary step for CIPP installation. Figure 3-1 shows some examples of pipe defects inside a sewer mainline.

Hole in pipe

Roots mass



Deformed pipe; multiple fractures; surface damage

Broken pipe (pieces missing)

**Figure 3-1: Pipe defects inside a sewer mainline (Navab, 2014)**

The conditions mentioned above make the cleaning phase a significant challenge given that the state of the pipe might obstruct the smooth operation of the equipment used, such as high speed water flusher, mechanical and/or robotic cutter and closed-circuit television (CCTV). Moreover, CIPP installation in sewers with flat surfaces, such as horseshoe-shaped sewers, egg-shaped sewers and non-circular sections in general, exhibit special design challenges (Abraham and Gillani, 1999; Lucie et al., 2014; Seeta et al., 2009). Broken and missing pipe, blockage due to debris and encrustation, and a significant amount of active infiltration are some common problems in aging sewer pipes (Ramirez et al., 2010) that may require costly spot repairs before the CIPP installation. In large diameter pipes, significant amounts of soft- and hard-sediment, calcification, tuberculation, malposition and leakage are common and may require man-entry repair (Wade et al., 2014). A project in New Jersey for the City of Newark Water and Sewer Authority faced significant issues due to different pipe configurations. In this project, the two sewer segments to be lined were linked by a common chamber in the middle of the run, and one of the biggest difficulties was to redirect the liner into the downstream sewer segment after it entered the chamber, which required the installation of a temporary diverting wall (Westervelt and Rodenberger, 2011).

#### ***3.3.1.2 Water Main***

An estimated 35% of water mains are more than 35 years old and as the water infrastructure in North America is older than the wastewater infrastructure (Selvakumar and Tafuri, 2012), the rehabilitation works of water distribution systems tend to be more problematic. As a result, in the United States market, an estimated 70% of rehabilitation projects are in the sewer sector, whereas only 30% are in the water sector (Selvakumar and Tafuri, 2012; Underground Construction, 2008). In addition, pipe preparation and cleaning of water mains for CIPP installation may also be difficult because of corrosion and thick encrustations. Over time, corrosion deposits build up on the inside walls of unlined pipes, resulting in tuberculation (Figure 3-2) (Wassam, 2015).

**Figure 3-2: Inside of the tuberculated pipe (Wassam, 2015)**

Tuberculation and protruding service fittings are two special problems in water mains for which cleaning is not possible, and corresponding mains need to be replaced prior to the CIPP installation (Deb et al., 1999; Matthews et al., 2012). Another common scenario is the variability of the interior diameters of water mains, which makes liner sizing difficult (Davison and Coté, 2015).

### *3.3.1.3 Lateral*

Each mile of mainline in the U.S. has 30 to 300 laterals (on average 75–85 per mile), and each lateral is an average length of 50 feet (WERF survey), meaning there are over 76 million sewer laterals in the U.S. alone (U.S. Census Bureau). Because of the abundant number of service laterals, lateral CIPP rehabilitation represents a significant cost. In addition, legal jurisdiction and private ownership issues aggravate this problem (Kristel et al., 2009). Ownership of sewer laterals differs considerably for municipalities even within a single metropolitan area, as shown in Figure 3-3 (Sterling et al., 2010). Therefore, municipalities are often hesitant to deal with infiltration and inflow problems from laterals by rehabilitation on the private side of the lateral (Tafuri and Selvakumar, 2002).

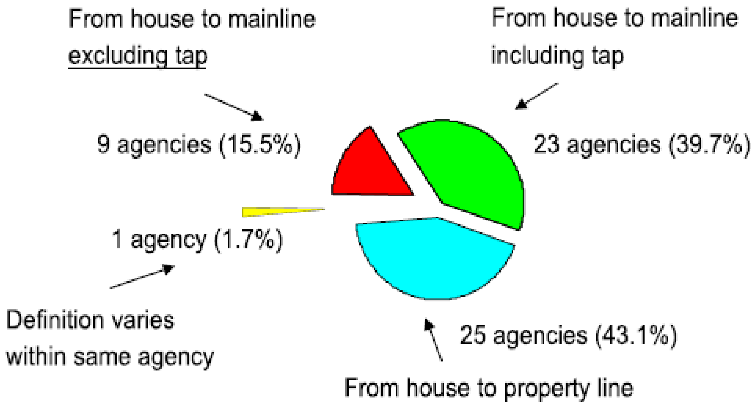


**Figure 3-3: Private ownership of sewer laterals (Sterling et al., 2010)**

CIPP installation in small diameter service laterals (4–6 inches) may be challenging (Wade and Johnson, 2007). Furthermore, sharp bends, transitions, and massive roots are common conditions in laterals and are difficult for CIPP installation. Some structural defects in lateral like hardened deposits and tuberculation may obstruct the cleaning phase of lateral CIPP projects (Belanger and Magill, 2015). Sometimes, the installation requires excavated point repairs due to settling and offset pipe sections (Hasan et al., 2014). Other times, different types of lateral-to-main pipe connections exist (tee, wye and double tee stack), which makes the CIPP process for laterals complex (Kiest and Hasan, 2014).

### 3.3.2 Pre-Installation

In Table 3-1, pre-installation challenges for different underground infrastructures are listed and discussed.

**Table 3-1: Issues prior to liner installation**

| System type | Pre-installation Challenges |
|---|---|

| | |
|---|---|
| **A. Sewer Main** | i. Presence of water intrusion due to infiltration/inflow (I/I).<br>ii. Requirement of temporary bypass due to the flow in the pipes and groundwater level.<br>iii. Temporary access road construction in case of sensitive areas.<br>iv. Access problems originating from smaller manhole diameter.<br>v. Inspection and cleaning issue for force mains.<br>vi. Requirement of special arrangement for resin impregnation in large diameter tubes.<br>vii. Challenging site access and layout. |
| **B. Water Main** | i. Access problems in water main pipes.<br>ii. Requirement of digging, shoring of pits and other open-cut activities.<br>iii. Incompatibility of the CIPP liners with the operation of the valves.<br>iv. Complicated plugging of service connections of water main over 1.5 inches. |
| **C. Lateral** | i. Difficulty accessing the cleanout.<br>ii. Access issue for cleaning and liner installation due to absence of cleanout.<br>iii. Probability of CCTV equipment blockage.<br>iv. Substantial and recurring root intrusion problems.<br>v. Infiltration issue prior to liner installation. |

Before the CIPP installation, if the pipe is subjected to infiltration/inflow (I/I) due to tidal and groundwater fluctuations, this may hinder the liner installation activities because the presence of water intrusion while trying to cure the liner may lead to delamination and curing problems. In this case, the most effective solution is chemical grouting of infiltration points in advance of the CIPP lining and installation of the pre-liner, but this results in a substantial cost (Cuellar and Yong, 2015). If the quantity of flow in pipes is significant and there is a high groundwater level, then a costly temporary drainage or bypass plan needs to be implemented (Liao et al., 2014). On occasion, surrounding conditions like densely populated and traffic congested areas make the bypass design more complicated and require additional costs (Ferguson et al., 2011; Westervelt and Rodenberger, 2011). Referring to issue (A.)(iii.) in Table 3-1, for some sensitive areas like wetlands and forests, transportation of liner and lining equipment is a significant concern and may require temporary access road construction before initiating CIPP installation (Ramirez et al., 2010). Another problem that may arise prior to sewer main CIPP installation is a small manhole diameter that causes access problems; suitable plugs should be created to address this issue (Liao et al., 2014). In the case of force mains, CIPP installation is more complex than gravity sewers because most force mains are in constant service, so they cannot be accessed internally for inspection without expensive by-passing arrangements, and cleaning prior to CIPP installation is often difficult (Murray, 2009). For issues (A.)(vi.) and (A.)(vii.) in Table 3-1, CIPP installation for a large diameter sewer main presents special problems. Because of the size of the liner and the significant weight of the resin, wetout at shop is not possible, and it requires special arrangements to impregnate or wetout the liner with resin onsite (Westervelt and Rodenberger, 2011). Additionally, site access and layout may be challenging for large diameter projects as they require some large pieces of equipment (e.g., resin tankers, cure control trailer, wetout tent, tractor trailer, etc.), and the resin tankers need access to come and go during wetout (Matthews, 2015). For instance, in a CIPP rehabilitation project in Los Angeles, California, the liner had to be transported in sections and seamed together before installation due to its size (seven layer felt tube and 1,800 feet long) (Hanks et al., 2010).

Installation of CIPP liners in water mains is more complex compared to sewer mains due to access problems of pressure mains (Matthews et al., 2015) and requirement of the flow to be shut down or bypassed, whereas gravity sewer flows can be diverted more easily (Hu et al., 2009). In order to gain access to the water main, access pits must be created (Figure 3-4). This requires digging and shoring, removal of the asphalt and concrete structure, and cutting six to eight feet of the exposed host pipe (Rosenberg and Anderson, 2015; Lueke et al., 2015). While the work is trenchless, it still requires a fair amount of digging and other open-cut activities during procedures like the installation of isolation valves and associated piping, the digging and shoring of pits, disposal of the cut away sections and the reinstatement of service pipe to water mains (Leitch et al., 2015). As CIPP liners are not compatible with the operation of valves, they must be replaced using open-cut (Wong et al., 2015). As a result, the locations of installation access pits are normally selected at existing valve boxes that will require replacement. For the case of (B.)(iv.) in Table 3-1, plugging and reinstatement of service connections over 1.5 inches is a particular problem. For example, before initiating CIPP installation, the service connections may need to be dug up rather than attempting to plug and reinstate them internally (Rosenberg and Anderson, 2015).

**Figure 3-4: Access pit with pipe removed (right) and bypass (left)(Matthews et al., 2015)**

Access is the main problem for CIPP liner installation in laterals if the liner is installed through cleanout. Most of the cleanouts, which are essential access points for lateral cleaning and installation, are located in backyard basements, making them difficult to access (Wade and Johnson, 2007). In addition, they are sometimes buried without markers which makes them hard to locate since they are almost always plastic. The problem will be more complex if there is no cleanout or access point in the service pipe. In this situation, the costly PVC saddles must be installed prior to cleaning and liner installation (Behe et al., 2012). Cleaning, measurement and inspection of laterals are some of the pre-installation key activities for which CCTV equipment is needed; however, where there are massive roots, heavy corrosion, and/or tap connection, the camera may become trapped in the lateral (Behe et al., 2012). If the lateral has substantial and recurring root intrusion problems, untreated roots can grow between the cured liner and host pipe, creating a larger annular space for underground infiltration and deformation of the liner. In this case, chemical root treatment should be employed prior to lining (Lee, 2006).

### 3.3.3 Challenges during Installation

Many issues may be observed during the liner installation phase. Table 3-2 shows the key challenges encountered during installation of CIPP liner for different water distribution and wastewater collection systems.

**Table 3-2: Issues during liner installation**

| System type | Challenges During Liner Installation |
|---|---|
| **A. Sewer Main** | i. Significant challenges for installing CIPP lining on long, steep slopes/pipes with severe elevation changes.<br>ii. Problems due to excess resin and improper impregnation.<br>iii. Construction hassles from too much heat in case of UV curing process.<br>iv. Long installation time for large diameter pipes.<br>v. Crystallization of the roots in the services because of resin migration in curing phase. |
| **B. Water Main** | i. Inaccurate installation pressure.<br>ii. Issues with using excess amount of resin.<br>iii. Problems originating from failure to maintain perfect combination between ambient temperatures at installation and pull rate. |
| **C. Lateral** | i. Noise disturbance to the occupant.<br>ii. Presence of air in the tube during onsite resin impregnation.<br>iii. Problems with water curing.<br>iv. Challenges to monitor the curing temperature perfectly in both upstream and downstream sides of the pipes.<br>v. Problems created from pipe sagging and improper curing during liner installation. |

Significant elevation changes have been known to cause problems during CIPP installation. For instance, the CIPP installation of combined sewer overflow (CSO) pipes by the Northeast Ohio Regional Sewer District (NEORSD) faced 45 feet elevation difference at one site and 60 feet elevation difference at another. Consequentially, the contractor handled considerable issues, including hydrostatic pressure on the downstream terminus of the CIPP liner, difficulty controlling the advancement of the CIPP liner on the steep slopes, and limited access to the downstream terminus of the CIPP liner. On one occasion, the downstream end/backstop failed during the installation of a larger diameter liner (Lucie et al., 2014).

In a sewer main CIPP installation by the City of Edmonton, the resin blew out from the liner due to the use of excess resin and improper impregnation (Edmonton site visit, 2014). In the case of UV curing process, allowing the temperature spike too high may melt the inner film and adhere to the inside of the liner, creating construction difficulties (Matthews, 2013).

For large diameter pipes, the length and diameter of the lining tube can considerably increase the installation time, as a significant amount of time is required for the curing process of large diameter tubes (Ramirez et al., 2010; Matthews, 2015). For instance, liner installation in the City of Los Angeles North Outfall Sewer (NOS), which is 78 inches in diameter and 1,800-feet long, took approximately seven days to complete (Hanks et al., 2010).

Handling of roots in the service is another obstacle that may occur during the liner curing process by resin migration that can crystallize the service roots which results in blockage. In addition, flooding can arise if this situation is not appropriately tackled (Abraham and Gillani, 1999).

During liner installation, monitoring the installation pressure is an additional key feature. For pressure pipe CIPP installations, variations in the installation pressure during curing may alter the end product quality. For instance, one study found that a higher installation pressure was the reason for a denser but thinner product. On the other hand, low installation pressures led to a less dense, thicker, but weaker liner (Davison and Coté, 2015).

A further important parameter during liner installation is the amount of resin used. The same study found that using excessive resin may result in blocking the service lines. Therefore, service reinstatement from the inside of the pipe will be challenging (Davison and Coté, 2015).

For the pull-in-place installation method, installation temperature and pull rate are two vital parameters. A recent installation in Carrboro, NC, observed that a combination of high temperature/humidity and unexpected pull loads resulted in a slower pull, and the increased temperature/humidity linked with the extra time required to pull the liner in place led to it gelling before it was installed. Consequently, a “C” shaped hardened liner stuck within the host pipe was the final product (Leitch et al., 2015). Similarly, in an AWWA water main installation, a nylon strap broke due to an unregulated rate of inversion and pulling (Deb et al., 1999).

Noise disturbance to the house occupants during lateral liner installation is a significant problem, especially if the liner is installed through a house cleanout. For lateral liners, the resin impregnation or wetout of the flexible tube is generally executed in the field, and many errors can occur during the process. For example, due to uncontrolled wetout, air that is left in the tube will led to spots of insufficient resin (Lee, 2006).

After inversion, ambient temperatures, hot water or steam can be employed to cure the lateral tube with resin systems. For lateral relining, ambient curing with air pressure is the most economic method with reduced equipment footprint. However, ambient cure time may range from two to twelve hours, whereas, liners can be cured as quickly as 30 minutes with steam curing. Therefore, steam curing is considered as the most productive curing method. On the other hand, water curing in laterals is not typically recommended as significant elevation change in lateral pipes results in higher inflation pressure at lower elevations that led to reduced liner thickness. Furthermore, hot-water curing in lateral pipes may reverse the inflation bladder that is filled with water (Kiest, 2011).

Referring to issues (C.)(iii.) and (C.)(iv.) in Table 3-2, one important parameter to consider when installing the CIPP liner is to monitor the curing temperature in both upstream and downstream sides of the pipe, but in laterals, readings are typically taken at the cleanout only. As a result, the curing temperature from the cleanout to the mainline pipe is unknown, which can cause heat sinks at various points due to groundwater infiltration and may cause defective liner installation in the line. Moreover, pipe sagging can cause pools of steam to collect and produce a thermal barrier and blistering, and lateral-to-main joints can create cold spots. If curing is not done properly and curing temperature is not monitored during liner installation, then all of these soft spots in the liner can result in lifts and blockages (Mathey and Rapp, 2015).

### 3.3.4 Post-Installation

This category discusses the deficiencies that may occur after liner installation. Table 3-3 shows post-installation challenges for water and sewer underground lines.

**Table 3-3: Post-installation challenges**

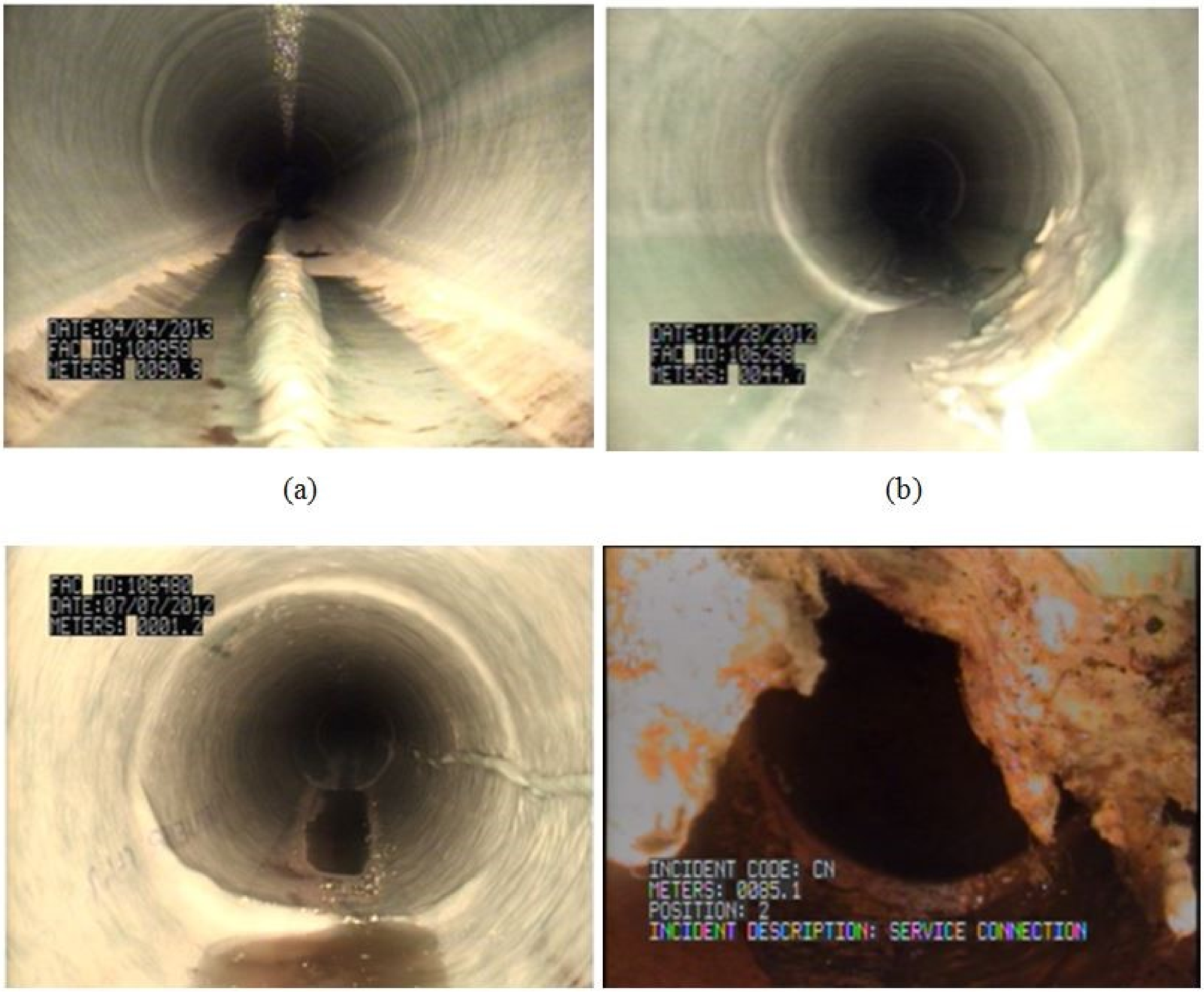
| System type | Post-Installation Challenges |
|---|---|
| **A. Sewer Main** | i. Issues of variable impregnation and curing, shrinkage due to polymerization and occurrence of wrinkles and folding.<br>ii. Variation of liner thickness within the existing pipe.<br>iii. Liner peeling due to improper sealing after vacuum impregnation.<br>iv. Water re-entering the system after mainline rehabilitation.<br>v. Reinstatement challenges due to high number of service connections in the sewer. |
| **B. Water Main** | i. Site restoration after CIPP installation, especially for AC water main.<br>ii. Occurrence of longitudinal fold after liner installation.<br>iii. Wrinkles and voids occurring.<br>iv. Variations in the host pipe diameter.<br>v. Reinstatement problems of smaller sized water main service pipe. |
| **C. Lateral** | i. Incidence of deficiencies like liner lift, peeling and wrinkles. |

The literature review shows a significant number of deficiency incidences following CIPP installation. Downey and Koo suggested that after CIPP installation, some fundamental issues require close attention, such as variable impregnation and curing, shrinkage due to polymerization, and wrinkling and folding, which may occur in CIPP at bends and at irregularities in the host pipe (Downey and Koo, 2015). In a CIPP project in the province of Quebec, problems with matching the manufactured liner with the existing pipe was a common issue found (Alzraiee et al., 2014). Liner thickness can change as a result of varying fabric thickness, inadequate resin, erroneous calibration of rollers during impregnation, higher than intended pressures during installation, and/or stretching of the fabric at steep downhill sections of the host pipe. A site visit to a CIPP project in Edmonton, Alberta, found evidence of liner peeling after the CCTV inspection, and a further study verified that liner peeling occurred exactly at a vacuum impregnation sealing spot (Navab, R., personal communication, April 30, 2015). This problem may arise due to improper sealing after vacuum impregnation and poor workmanship (Figure 3-5). Addressing liner peeling required a costly spot repair.

(a) (b) (c)

**Figure 3-5: (a) Vacuum impregnation and sealing, (b) liner peeling and (c) spot repair (Navab, R., personal communication, April 30, 2015)**

Figure 3-6 shows different examples of post-installation liner deficiencies collected from sewer main CIPP installation projects in Edmonton, Alberta. There is evidence of water re-entering the system post-main line rehabilitation in a CIPP project by the City of Coral Gables in Miami-Dade County (Hasan et al., 2014). If the lateral and main joint is not repaired, then infiltrated water through the joint may weaken the installed liner and the host pipe integrity. Another important issue after CIPP installation is the high number of service connections in the sewer system, which require a significant amount of time to reinstate (Stein, 2005). Service connections are reinstated by cutting a hole in the liner at the spot of each lateral pipe and those cutouts are typically the only breaks in the continuity of the liner between manholes. Sometimes, it is usual for the cutouts to be uneven, overcut, or undercut, and therefore not the same size and shape as the lateral pipe (Pennington et al., 2005) and it is recommended to install short tee connection liners in these locations. In small, non-man-entry sewers, this is a difficult problem to overcome because the work is done with robotic cutters and trimmers, although there are some new technologies (such as utilizing sensors and/or LED indicators) that can address these situations.



(a) (b)

(c) (d)

**Figure 3-6: Different liner deficiency of sewer main CIPP: (a) fold in liner ( b) liner peeling (c) wrinkles or bubbles and (d) service undercut (Source: CIPP installation projects in Edmonton, Alberta)**

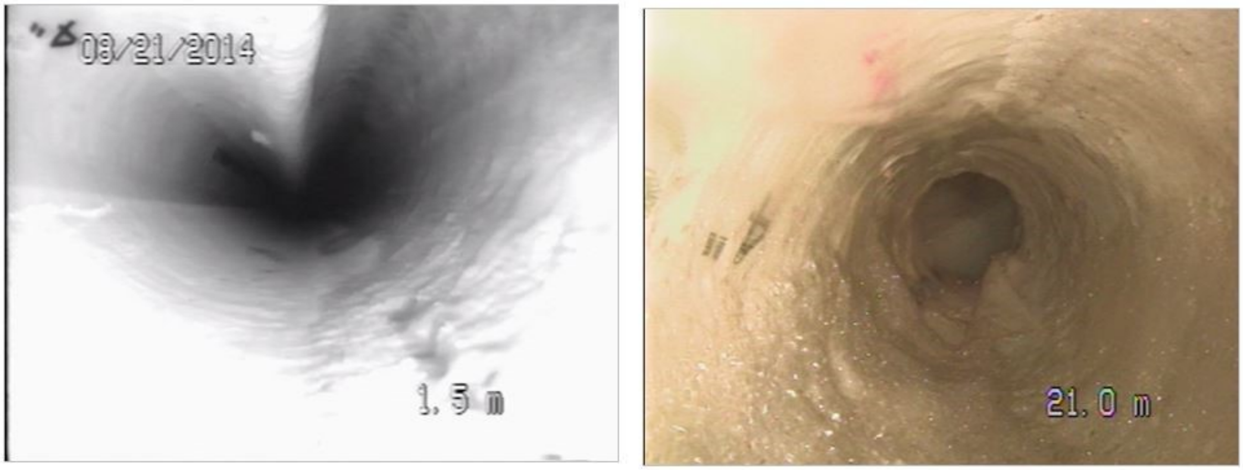
A particular challenge for water mains is site restoration after CIPP installation, which is achieved by backfilling the access pits, concrete repair/replacement, asphalt paving of the roadway, and restoration of any green space that was disturbed. As shown in Figure 3-7, after successful CIPP installation, lined pipe sections should be connected by PVC pipe (Matthews et al., 2015).

Figure 3-7: Lined  pipe sections connected by PVC pipe (Matthews et al., 2015)

A study by Michael Davison and Ben Coté shows the occurrence of a fairly large longitudinal fold after liner installation that hinders the use of reinstatement and CCTV equipment (Davison and Coté, 2015). In an experimental testing and numerical modeling study undertaken to evaluate the impact of a longitudinal fold on the ability of a CIPP liner to resist internal pressures resulted in high stress concentrations that develops along longitudinal folds. However, potentially undesirable effects can be alleviated by controlling the oversizing of the virgin liner. This study proposed a quality control (QC) criterion named ‘‘allowable oversizing ratio (AOR)’’ which is a function of the pipe’s internal diameter, gap dimensions and surge to disregard the risk of premature failure initiated from longitudinal folds (Jaganathan et al., 2007).

Other common post-installation deficiencies are wrinkles and voids. A project in Kitchener, Ontario, discovered wrinkles and voids, and an internal wrinkle within the liner lapsed over a portion of internal service connections. This prevented the robotic cutter from identifying the location of those connections, requiring open-cut excavation and installation of such service connections (Wong et al., 2015). In addition, a study by AWWA shows that variations in the host pipe diameter (caused by replacing pipe material with material of a slightly smaller diameter) caused wrinkles after liner installation (Deb et al., 1999). Wrinkles are typically occurred if the external circumference of the liner exceeds the internal circumference of the host pipe. From split-disk test on samples obtained from lined cast iron pipes exhumed from a field site in Hamilton, Canada, it was evident that failures of liners took place at or in the vicinity of the wrinkles and as the wrinkle size enlarged, the ultimate strength of the liner and its strength at first cracking were decreased (Ampiah et al., 2008). A further important issue after water main CIPP installation is the reinstatement of a smaller sized service pipe, as the necessary equipment to reinstate smaller service pipes (as small as half an inch) from a smaller size water main (less than or equal to 6 inches) is limited (Davison and Coté, 2015).

Several post-installation deficiencies, like liner fold, lift, peeling and wrinkles, are significant issues for lateral CIPP installation projects. These kinds of deficiencies need spot repairs with significant cost. Figure 3-8 provides deficiencies in lateral liner (liner fold and peeling) found from CCTV inspection after CIPP installation at Edmonton city lateral rehabilitation projects.



(a) (b)

**Figure 3-8: Post-installation deficiencies in lateral: (a) fold in liner, (b) liner peeling (Source: lateral relining projects in Edmonton, Alberta)**

### 3.3.5 Environmental Challenges

Despite widespread and frequent use of CIPP, the environmental impact of CIPP technology on surface water or aquatic habitat has not been sufficiently investigated (Donaldson, 2009). Environmental challenges are basically applicable for culvert and storm water drainage pipes that have water sources downstream. Table 3-4 shows the environmental issues regarding CIPP installation.

**Table 3-4: Environmental issues of CIPP installation**

| **System type** | **Environmental Challenges** |
|---|---|
| **Culvert and storm water drainage pipe** | i. Post-installation chemical emissions and effluent leaked/discharged.<br>ii. Issues of styrene used in the resin complex, which is poisonous for aquatic habitats.<br>iii. Fish deaths due to the spills of uncured resin from CIPP installations.<br>iv. Presence of different carcinogenic chemicals.<br>v. Elevated COD, VOC and metal levels due to CIPP condensate. |

Potential negative environmental impacts originate from the resins and effluent leaked or discharged downstream or from chemicals trickled from the cured pipe after the installation is accomplished (Donaldson, 2009; Downey and Koo, 2015). Of particular apprehension are the potential effects of styrene, which is usually used as a significant component of the polyester resin and vinyl ester resin that saturate the lining tube. Environmental concern is typically for CIPP installations that use styrene with resin systems while styrene free resin systems (such as vinyl toluene based vinyl ester resin and epoxy resin) and UV liners are environmentally safe. U.S. Environmental Protection Agency (EPA) has classified styrene as a mutagen and considered as potentially carcinogenic. For aquatic species styrene may be noxious if beyond certain concentrations (Donaldson, 2009; Baer et al., 2002). Although most of the CIPP installation projects of storm sewers are successful, literature reveals that spills of uncured resin in just a small number of CIPP installations resulted in large fish kills.

For instance, about three to four gallons of uncured resin was released in the course of a CIPP installation on a storm water drain; the residual uncured resins were conveyed to a creek, causing the death of more than 5,500 fish of several species (Donaldson, 2009). There was also evidence of a fish kill in British Columbia due to styrene released after CIPP installation (Lee, 2008). A study conducted by the Virginia Department of Transportation (VDOT) suggested that at certain times after CIPP installation, styrene concentrations exceeded the Maximum Contaminant Level (MCL) for drinking water at five of the seven study sites. It also exceeded the 48-hour effective concentration (EC50) and 96-hour lethal concentration (LC50) values of the water flea and the rainbow trout, respectively, at four of the monitored project sites. LC50 and EC50 represent the concentration required to kill (LC50) or have a defined effect (EC50) on 50% of the test population after a given number of hours' exposure in that concentration. The highest styrene concentration recorded was 77 mg/L, which is far higher than standard styrene toxicities for different aquatic species (Donaldson, 2009). A recent study of the downstream water following a CIPP installation identified not only styrene, but other carcinogenic chemicals, including ethyl ketone, isopropylbenzene, n-propylbenzene, 1,3,5-trimethylbenzene acetone, 4-tert-butyl-cyclohexanol, and 4-tert-butylcyclohexanone (Tabor et al., 2014). In the same study, results indicated that CIPP condensate had elevated levels of metal, Chemical Oxygen Demand (COD) and Volatile Organic Contaminant (VOC) and was acutely toxic to water species. COD and Total Organic Carbon (TOC) monitoring results denoted that organic materials remained in the environment for at least 35 days after CIPP installations. In order to prevent the unintentional release of styrene-based resin during installation and the leaching of styrene from the finished product, VDOT recommended new CIPP specifications (Donaldson, 2009). The attainment of discharge-related permits, including air, water, and wastewater treatment; dry installations (i.e., no water is contained or conveyed in the pipe during installation); supplementary lining materials and measures to safeguard the containment of resin and styrene; comprehensive rinsing of the finished product; appropriate disposal of cure water, cure condensate, and rinsate; and requirements for water and soil testing before and after installation are some of the examples from new CIPP specifications by VDOT (Donaldson, 2009).

## 3.4 Remarks and Discussion

In this study, issues and challenges that may occur in a CIPP project have been divided into five different categories. Based on the systematic review in this field, the following problems were identified and corresponding suggestions are tentatively made for future research:

- Aging and deteriorating infrastructure conditions such as cracks, internal corrosion, grease build-up, root intrusion, joint misalignment, separation, leakage, excessive pipe deflection and lateral connection leakage are significant concerns for the preliminary step (i.e. cleaning) in the CIPP process. Cleaning of severely corroded concrete sewers and tuberculated water mains is a major challenge. Further emphasis should be put on introducing more innovative cleaning equipment.

- There is no specific design standard for CIPP installation in sewers with non-circular sections. More research is needed on this topic.
- Lateral CIPP rehabilitation is always challenging due to small diameters, sharp bends, transitions, root intrusion, legal jurisdiction, and other issues. Future research is recommended to make the lateral CIPP process more efficient and effective.
- Due to tidal and groundwater fluctuations and high flow, more work may be conducted on temporary bypass designs, drainage plans, and pre-liner installation or chemical grouting of pipe joints in advance of the CIPP lining for pipes subjected to infiltration/inflow (I/I).
- Installing CIPP for large diameter sewers involves special problems such as onsite wetout, site access, equipment layout, long installation and curing time. Adequate planning and careful attention are required to ensure proper and timely preparation in advance of the lining equipment set-up, site access and layout.
- During liner installation by air inversion, finding an appropriate installation pressure is a key issue. For pull-in-place installation, it is necessary to maintain a good balance between installation temperatures and pull rate.
- Another significant challenge in lateral liner installation is to monitor the curing temperature in both upstream and downstream sides of the pipe. Readings are typically taken at the cleanout only. Recently there are some sensors available to mitigate this issue.
- Different post-installation liner deficiencies like folds, liner peeling, wrinkles or bubbles are common in CIPP projects. Further research may be conducted to investigate these problems and find effective ways to mitigate them.

For storm sewers, potential environmental impacts of chemical emissions derive from the resins and effluent leaked or discharged to downstream water sources. The major concern is styrene, which is one of the most significant resin components of polyester resin and vinyl ester resin. Therefore, during the CIPP rehabilitation of culvert or storm water drainage pipes that convey streams or storm waters to downstream water sources, there should have stringent rules against styrene usage and different styrene free options like epoxy resin and vinyl toluene based vinyl ester resin should be used that are environmentally friendly.

## 3.5 Conclusion

As the nation's infrastructure continues to deteriorate, the use of CIPP rehabilitation technology becomes more attractive. However, relining using CIPP may be accompanied by a number of issues and challenges; hence, many potential advancements in the application of CIPP technology remain. This systematic review provides a concise but comprehensive summary of information needed by researchers and engineers to understand challenges that may arise during CIPP installation work. In this study, the challenges that may occur in a water and wastewater infrastructure CIPP project have been divided into five different categories. This research may benefit trenchless CIPP companies and water distribution and wastewater municipality sectors.

# Chapter 4: Productivity Analysis of CIPP Sewer Main Rehabilitation Projects

## 4.1 Introduction

Renewal of damaged and worn pipes is becoming a significant maintenance concern for municipalities in North America as many collection systems have reached beyond their service lives. Cured-in-place pipe (CIPP) rehabilitation is one of the most common trenchless technologies, allowing users to renew existing underground pipes without using open cut methods. A significant amount of CIPP sewer main projects are associated with large diameter pipes (greater than or equal to 375 mm), which are considered more challenging due to high flow, deeper access pits or manholes, potentially thicker calcite inside the pipe, etc. Executing a project of large diameter pipes requires meticulous and timely planning in order to prepare for lining equipment setup and site access for large pieces of equipment (cure control trailer, truck trailer, etc.), especially when a project has multiple installation shots (Matthews, 2015). Therefore, relining large diameter sewer mains is not a straightforward process, and it is associated with a number of uncertainties that affect the productivity of a project.

Although productivity is the most significant factor for the planning and budget allocation of CIPP projects, there is limited information on the topic in literature. For municipalities to establish an efficient asset management program, productivity data is crucial. This study describes the CIPP process and conducts a productivity analysis of 44 large diameter (greater than or equal to 375 mm) sewer pipeline rehabilitation projects in Edmonton, Alberta, rehabilitated through the CIPP inversion process. This research illustrates how varying pipe diameters and liner thicknesses affect productivity of the CIPP lining process. The time and number of crew members required for different steps in the CIPP process have been tracked to determine productivity. Corresponding results may be used to assist contractors and engineers in estimating project costs and schedules.

## 4.2 CIPP Methodology

Due to ever increasing labor, energy, and machinery costs, it is becoming increasingly difficult and uneconomical to repair underground facilities by excavation and install new pipes to replace old ones (Delaney et al., 2007). For this reason, several methods of in-place repair or rehabilitation have been invented to avoid the expenses and hazards associated with digging up and replacing pipes or pipe sections, as well as to avoid significantly disturbing the public. One of the most successful pipeline repair or trenchless rehabilitation processes currently in use is CIPP. This trenchless rehabilitation technology allows placing new pipe within the original pipe with stand-alone structural characteristics while eliminating infiltration and exfiltration through open joints, holes and fractures at a reduced cost, in less time, and with fewer inconveniences to the owners and surrounding community ("Lanzo Lining Services Inc.," 2010). According to ASTM F1216, CIPP is defined as a technique to reconstruct pipelines and conduits by the installation of a resin-impregnated, flexible tube, which is inverted into the existing conduit by utilizing a hydrostatic head or air pressure. The resin is cured by circulating hot water or providing controlled steam within the tube, and after curing, the finished pipe will be continuous and tight-fitting (ASTM, 2007). Pipe preparation, wetout, and relining are the three significant phases of the CIPP process. To perform a productivity analysis, it is necessary to break down the different activities associated with CIPP. The following diagram shows the activities associated with air inversion and steam cure CIPP methods conducted by IVIS Inc. in Edmonton, Alberta.

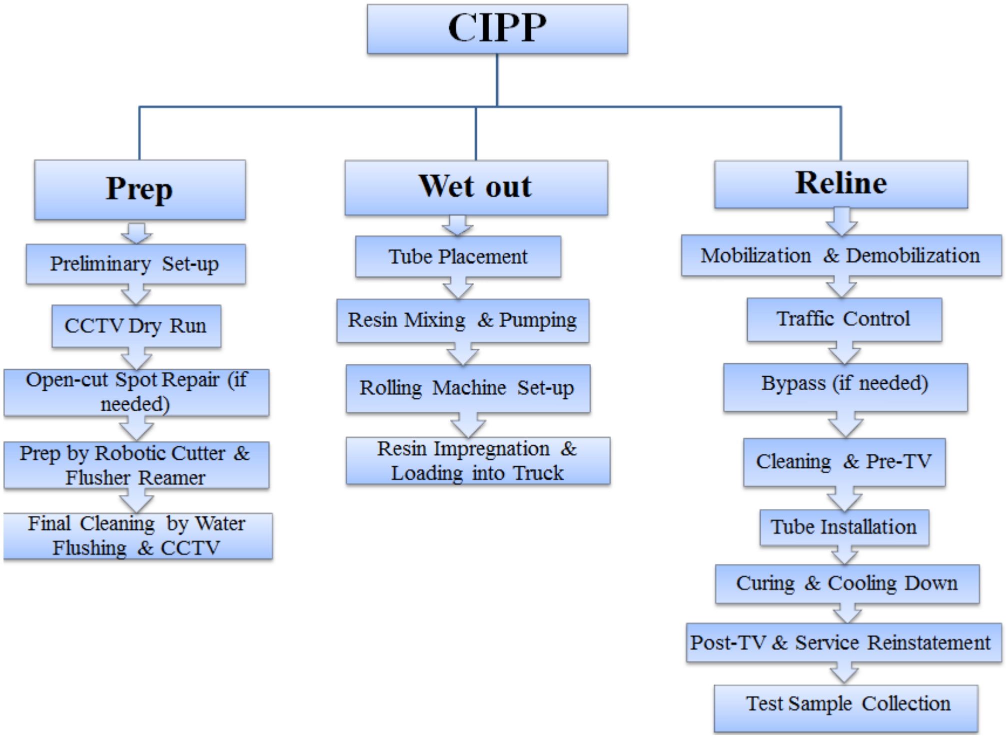


**Figure 4-1: Branch diagram of different CIPP steps**

In the initial step of the prep process, existing pipe must be CCTV-inspected for debris, roots, damage, offset joints, or any other incongruity that may impede proper CIPP installation. Inspection also requires measuring the pipe diameter, pipe length, and manhole depths, as well as recording the pipe location and other important conditions (e.g. overhead power lines, railway, backyard easement, excessive sewerage flows, etc.) for planning purposes. Pipe preparation may apply internal mechanical cleaning and grinding to remove roots, protruding laterals, encrustations, or other impediments in the pipe. Collapsed pipe or severely offset joints (i.e. 40% of the diameter) typically require point excavations at those locations while loose dirt, debris, or tuberculation may involve high pressure water or mechanical cleaning with a final pre-lining inspection of the pipe's entire circumference ("Lanzo Lining Services Inc.," 2010).

After a tube of proper diameter and thickness has been matched to the original host pipe, the CIPP process moves forward with resin-impregnation, which is referred to as the wetout process. Generally, liner preparation and resin saturation take place in the controlled environment of a workshop, where the resin and tube temperatures are regulated so that the resin does not start to cook. The resin-saturated tube should be refrigerated to slow the chemical reaction and provide additional safety during the transportation and installation of the liner. To prepare the tube, air must first be evacuated to create conditions for vacuum impregnation, and then the catalyzed resin is introduced into the tube under vacuum conditions so that air is completely displaced with resin while the resin saturates the fabric. The tube is then put through a pinch roller set to an appropriate thickness so that a standard amount of resin is introduced into the tube. The resin volume should be adequate to fill all voids in the tube material at nominal thickness and diameter. 5–10% excess resin should be added to accommodate the change in resin volume due to polymerization and to allow for any migration of resin into the cracks and joints of the original pipe (ASTM, 2007). Finally, the tube is loaded into a refrigerated truck for transportation to the jobsite. In the case of man-entry pipes, the wetout process may take place at the construction site, where the liner will go from wetout directly into the original pipe, as the tube with saturated resin becomes too heavy to transport. If properly handled and stored, resin-saturated tubes may remain stable for over a week ("Lanzo Lining Services Inc.," 2010).

During the relining step, the resin-saturated tube can be installed through an existing manhole or other approved access point by either the pull in, water or air inversion method. This study addresses the air inversion process. The application of air pressure should be adequate to fully extend the tube to the next specified manhole or closure point and to hold the tube tight to the pipe wall. As the tube enters the guide chute, the tube should be turned inside out so that the woven and nonwoven materials are not subject to overstress from the applied air pressure (ASTM, 2007).

After installation, the tube is cured via circulation of heated water, introduction of steam, or the use of ultraviolet (UV) light. In this study, all liners have been cured with steam. The foremost drawback associated with water inversion and curing is the quantity and availability of the inversion water. In this process, water is typically heated to affect the cure and then cooled with additional cold water according to resin and tube provider descriptions and ASTM standards before being released to an acceptable disposal system. This shortcoming may be resolved with the use of air instead of water to create the inverting force. Once the inversion of a resin-impregnated tube is fully accomplished, it is cured with the introduction of steam. Although water is essential to generate steam, the amount of water in the form of steam is only 5–10% of that entailed for water inversion, cure, and cool down (Delaney et al., 2007). Almost entirely, the tube is cured in a two-staged heating process and cooled in a regulated approach to a temperature below 120°F. Initial cure will occur during temperature heat-up and is achieved when exposed portions of the new pipe seem hard and the remote temperature sensors at the interface designate that the required temperature for exotherm or cure in the resin has been reached. After initial cure, the temperature is elevated to a post-cure temperature and held for a designated period as suggested by the resin manufacturer (ASTM, 2007).

According to ASTM specifications, the finished pipe should be continuous over the complete length of an inversion run and free of dry spots, lifts, and delaminations. Once installed, cured, and cooled, the CIPP is fully opened on both ends while any lateral connections leading to the pipe are reinstated with remotely operated cutting machines. This is followed by a final CCTV inspection and sample collection based on ASTM standards. In this study, as the sample collection is part of the reline process, time analysis of the installation includes the time spent on collecting the samples.

## 4.3 Productivity Analysis

Productivity is expressed as the ratio of work output to work input, which can also be designated as performance factor, production rate, and man-hour rate. Traditionally, productivity is measured in two ways: by the labor or crew performance required to complete a job unit, or by the amount of the job finished by a labor or a crew in a given time and place (Navab, 2014). For the CIPP process, productivity can be measured in two units: man-hours to complete one foot of mainline (mhr/ft), or the length (ft) of mainline completed by one man-hour (ft/ mhr). The following sections detail the productivity analysis conducted on the three significant steps of the CIPP process.

### 4.3.1 Pipe Preparation

In this section, the City of Edmonton's Queen Alexandra neighbourhood reline projects (total of 22 pipes) for large diameter pipes, conducted by IVIS Inc., is considered for pipe preparation (prep) productivity analysis. Prep mainly depends on a pipe's physical and operational conditions that can be gathered from sewer condition inspection reports provided by municipalities. This report typically provides start and end manhole information, size, length, shape and material of pipe, sewer type, and CCTV survey information. Before tube installation, the pipe must be free from any kind of severe debris, roots, damage, aggressive offset joints, encrustations, and service connection problems.

Prep is the preliminary step in the CIPP process. It begins with the setup of the cutter crawler and flusher chain saw nozzle according to the diameter of the selected pipe, which requires about 25–30 minutes. A dry run of the CCTV camera is then conducted to inspect the defects of the pipe and identify their locations. After that, all heavy roots, debris, encrustations, and protruding laterals are cut with either a flusher nozzle or remote-controlled robotic cutter crawler attached to the CCTV camera. Of the two methods, the flusher nozzle is two times more productive, but the cutter crawler offers its operator increased control, particularity in cutting protruding PVC. Once the pipe is cleared via flusher nozzle or cutter crawler, CCTV inspection is performed and the pipe is cleaned with a high-pressure water jet, which can be accomplished at an average rate of 5 m/minute. The above information was collected from the site visit with the prep crew of IVIS Inc.

Figure 4-2 shows the average productivity (ft/mhr), along with maximum and minimum values for the overall prep process of different City of Edmonton projects with respect to different pipe diameters. In all selected projects, the prep crew consisted of three members. As the pipe size increases, the average prep productivity decreases due to greater time requirements for prep completion. Generally, larger pipes are associated with higher prep time due to thicker encrustation requiring greater cutting time. Although there is a decreasing trend in the mean prep productivity, it is evident that a significant variation exists between the maximum and minimum prep productivity values associated with each diameter. The most significant factor for variations in the prep productivity value is the pipe condition and number of service connections. Generally, the more debris, roots, damage, offset joints, and service connection problems, the more time it takes to complete the prep operation.

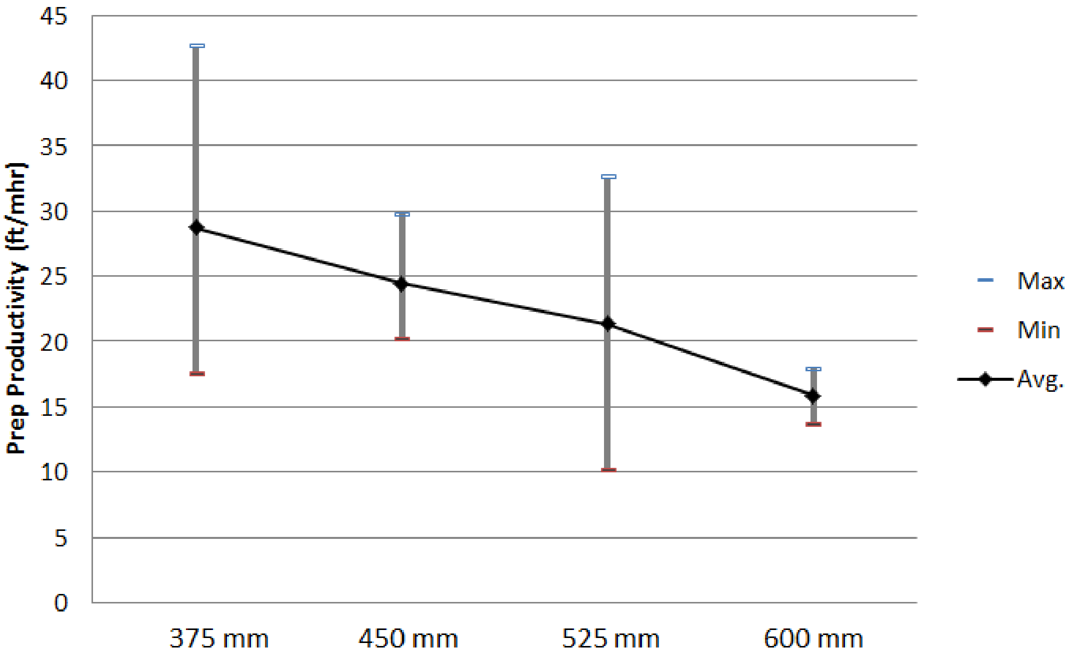


**Figure 4-2: Average prep productivity for different pipe diameters**

### 4.3.2 Wetout

Typically, the wetout process is accomplished in a wetout shop to ensure proper quality control. According to data collected from IVIS Inc., the percentage of time associated with different wetout steps has been shown in Figure 4-3. From this, it is evident that resin mixing and resin impregnation are the two most significant steps in the wetout process. Conversely, tube placement and machine set-up require a much smaller amount of time.

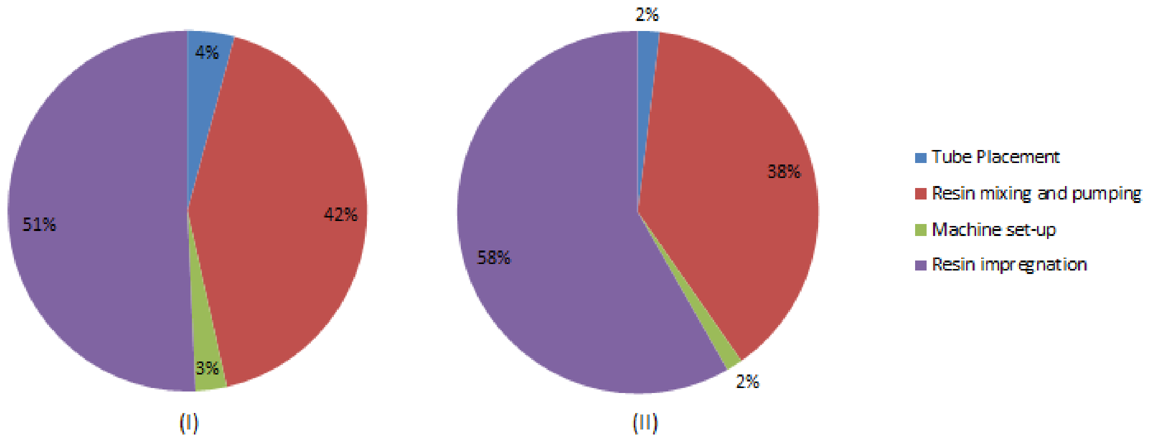


**Figure 4-3: Distribution of time spent on wetout steps for (I) 375 mm and (II) 600 mm diameter pipe, respectively**

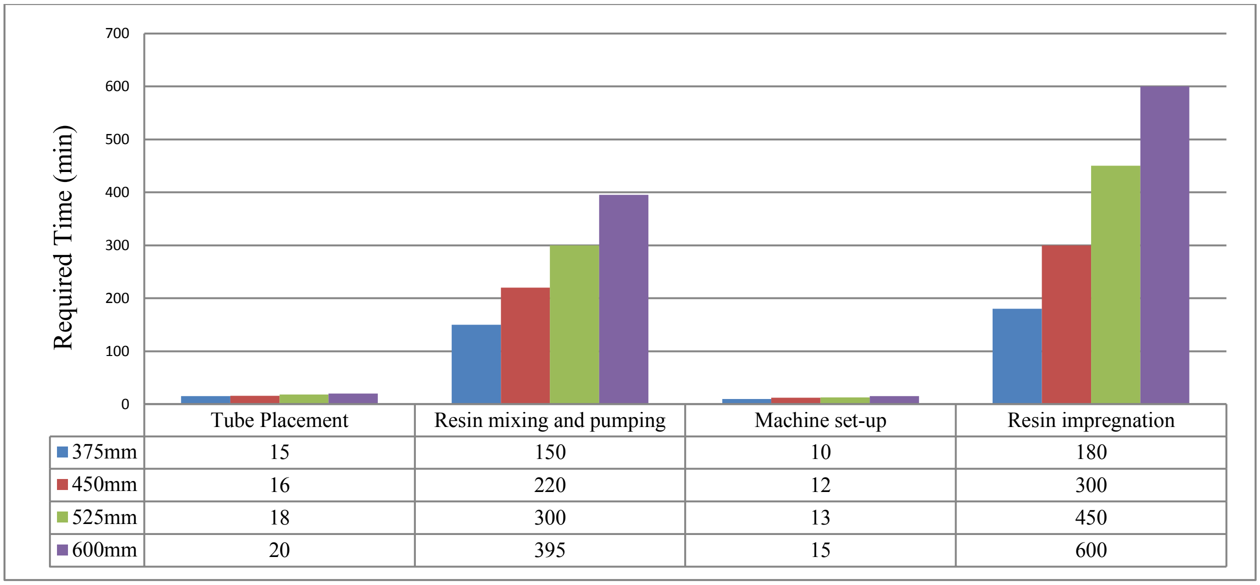
For a consistent productivity analysis, a constant tube length of 980 ft has been used. Additionally, the corresponding number of resin drums required for different tube diameters is calculated by considering that resin thickness is equal to liner thickness with 5–10% excess resin, as per ASTM F1216 (ASTM, 2007). The Interplastic Corporation provides the mixing amount of catalyst with respect to liner thickness for hot air initiation cooking systems in Table 4-1 (Navab, R., personal communication, October 15, 2014):

**Table 4-1: Amount of catalyst for mixing with neat thermoset polyester or vinyl ester resins for different liner thickness**

| Liner Thickness (mm) | Catalyst A (phr) | Catalyst B (phr) |
|---|---|---|
| 0-10 | 1 | 0.3 |
| 10-18 | 0.8 | 0.2 |

Where “Catalyst A” could be perkadox 16, trigonox 121-BB75 or equivalants, and “Catalyst B” could be trigonox C, 42S, KSM, 21, 21C50, 21OP50 or equivalents.

Based on visits to the wetout shop, it was calculated that each drum (520 lb) of resin mixing with catalyst and pumping into the tube required approximately 10 minutes and two minutes, respectively. The identified times can be used to calculate resin mixing and pumping time through multiplication with the number of resin drums required for different pipe diameters. The most significant contributing factor for resin impregnation in the tube is the roller speed. As the tube size increases, roller speed decreases due to the heavier tube requiring greater time for resin impregnation. In this analysis, resin impregnation time is calculated from roller speeds provided by experts in the wetout shop. The following figure shows that the required time for individual wetout steps is greater for larger diameter tubes; however, for tube placement and machine set-up, it is virtually constant and, consequently, insignificant.



| | Tube Placement | Resin mixing and pumping | Machine set-up | Resin impregnation |
|---|---|---|---|---|
| 🟦 375mm | 15 | 150 | 10 | 180 |
| 🟥 450mm | 16 | 220 | 12 | 300 |
| 🟩 525mm | 18 | 300 | 13 | 450 |
| 🟪 600mm | 20 | 395 | 15 | 600 |

**Figure 4-4: Required time for individual wetout steps with respect to different diameters**

Provided that the wetout crew consists of four members, the wetout productivity (ft/mhr) can be found. From Figure 4-5, it can be concluded that smaller diameter tubes have a higher associated productivity rate than larger ones. The wetout crew for a 600-mm diameter tube should anticipate about three times more required time to accomplish the wetout process than a crew for a 375-mm diameter tube.

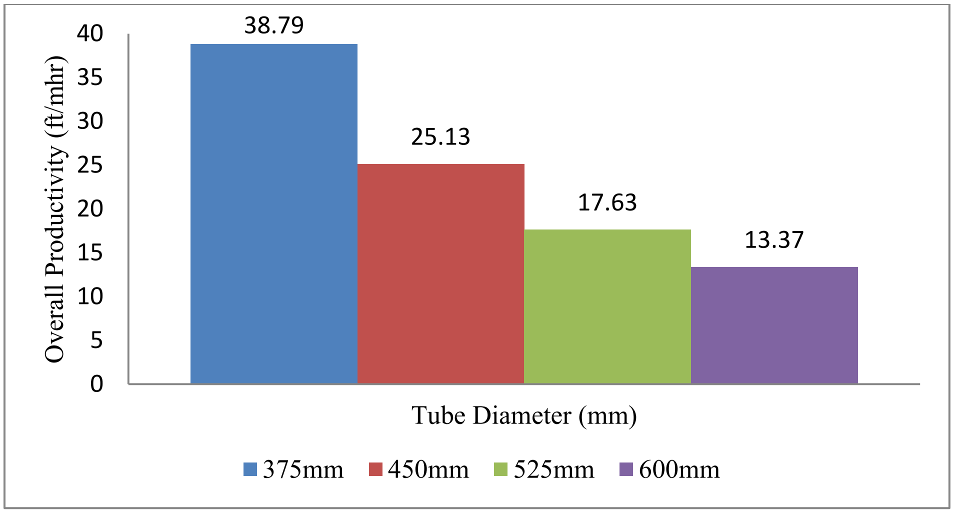


**Figure 4-5: Overall productivity of wetout process for different diameters**

### 4.3.3 Reline

Relining is the most significant step of the CIPP process. It consists of equipment mobilization and demobilization, log creation, traffic control, pipe cleaning and pre-TV, tube installation, curing, post-TV, and service reinstatement. After equipment mobilization, a site inspection and hazard assessment log is filled up, which requires approximately 5–10 minutes. One of the crews also fills up the cook sheet (curing log) when the curing process is taking place. Figure 4-6 shows the percentage of time for each relining step as collected from site visits to observe crew activity. It is evident from the figure that the curing step accounts for more than 50% of the total time required for the entire relining process. As is evident in the figure, the other steps, excluding liner installation, require only a small amount of time. With an experienced crew and improved equipment, liner installation can be relatively quick. However, liner curing and cooling require the most significant amount of time in the relining process. As a result, this study only considers curing and cooling time for productivity analysis, as this represents a significant portion of time for the relining process.

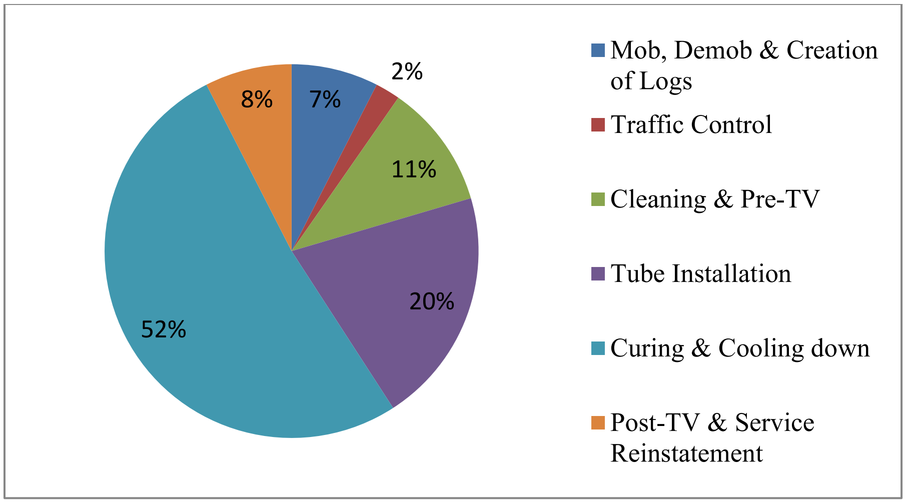


**Figure 4-6: Percentage of time associated with different reline steps**

In this study, the curing process is conducted through a two-stage cooking process. According to the cook sheet report, the temperature is initially increased to 130°F, which is considered an ideal initial cure temperature. Finally in the second stage, the tube reaches the post-cure temperature at 150°F. Care should be taken so that the temperature and pressure in the tube remains below the bursting temperature and pressure. Temperature can be controlled by modifying air pressure from the compressor and steam flow from the boiler truck. After achieving maximum peak exotherm, the cooling down process should begin, and the temperature is decreased to 120°F within 30 minutes for felt thickness less than 10 mm. This process should take no less than 40 minutes for felt thickness within 10 to 18 mm (Navab, R., personal communication, October 15, 2014).

A total of 44 large diameter liner installation projects located in different neighborhoods around Edmonton have been considered for this analysis. From Figure 4-7, it can be concluded that an increase in pipe diameter decreases curing production (meter per minute). Moreover, for each particular pipe diameter, a higher liner thickness is associated with a lower production rate (i.e. increased amount of time required to complete the process). To reduce cooking time and increase productivity rate, crews can consider the use of a double compressor for large diameter pipes.

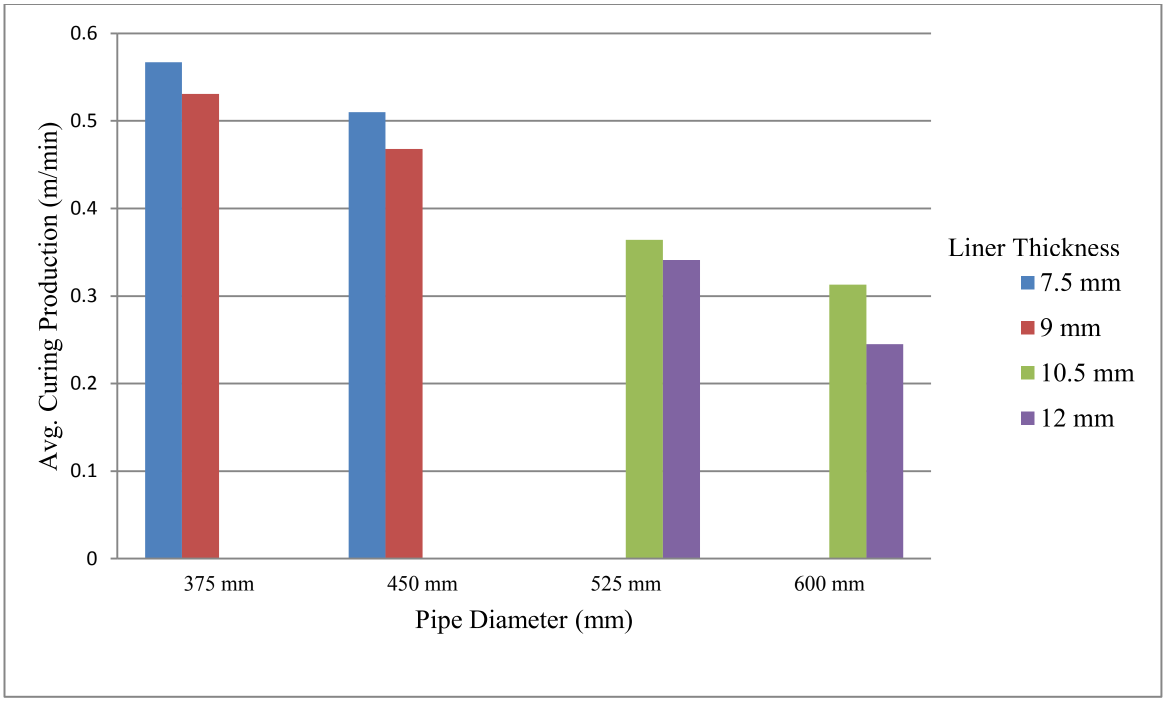


**Figure 4-7: Variation of curing production for different pipe diameter and liner thickness**

## 4.4 Conclusion

This research discusses the productivity analysis of the CIPP method in sewer mainline rehabilitations using collected data from large diameter CIPP liner installations in different neighborhoods in Edmonton, Alberta. The selected pipe size varies from 375 mm to 600 mm, and the installed liner thickness is from 7.5 mm to 12 mm. This study breaks down the CIPP process into three major activities (steps) of pipe preparation, wetout, and relining and explains the procedure of each activity in detail.

This study determines the time allotment of different reline steps in the CIPP method and compares the production rate of CIPP installation in connection with different pipe sizes. This research also analyzes the effect pipe size and liner thickness have in implementing each major step in the CIPP process. In future study, extra data collection from different areas would be required to validate this study. Also, it would be helpful to analyze other productivity factors such as workers' experience, environmental factors, and equipment in the CIPP process.

# Chapter 5: Productivity Analysis of Lateral CIPP Rehabilitation Process by Using Simphony Simulation Modelling System

## 5.1 Introduction

Sewer laterals are the private portion of the sewer network connecting individual and private properties to the public sewer system. Laterals are often in poor condition, and this can have a significant impact on the performance of the sewer system and treatment plants. Cracked or broken laterals can allow groundwater and infiltrating rainwater (clean water) to enter into the sewer system which, at high levels, can result in higher demands at the treatment facility or overload the sewers and produce sanitary sewer overflows (SSOs) (Sterling et al., 2010).

The condition of sewer laterals can also affect the results of sewer system rehabilitation programs, particularly those programs investigating and addressing inflow and infiltration (I&I) and capacity issues. Until the laterals are also fixed, repairing or replacing sewer mains to remove infiltration may be less effective in reducing I&I than predicted (Sterling et al., 2010). Literature reveals that performing only sewer mainline rehabilitation may not be effective for I&I reduction. The Oak Valley neighborhood of Nashville, Tennessee, is one example where a regression analysis was used to compare I&I reduction from pre-mainline rehabilitation, post-mainline rehabilitation, and post-lateral rehabilitation. The outcomes suggested that only mainline rehabilitation results in a 52% reduction in peak hourly flow, whereas combined lateral and mainline rehabilitation resulted in an 84% improved reduction of pre-rehabilitation flow (Simicevic and Sterling, 2006a). Therefore, achieving an efficient wastewater collection system and an effective overflow elimination strategy may require both sewer mainline and lateral rehabilitations. Typically, private laterals make up about half of the total length of a sewer system (Sterling et al., 2010). Even when the system-wide consequence of infiltration is not a concern, defective laterals can cause raw sewage to backup into homes and businesses, create unhealthy situations and can be a notable issue of apprehension in public works agencies. Consequently, lateral rehabilitation is of great importance for an effective sewer system rehabilitation program.

Among the different trenchless lateral rehabilitation techniques, cured-in-place (CIP) lining is considered a safer, less disruptive, more efficient and productive alternative to other methods. Various types of CIP lateral liner may be practicable depending on the type of lateral-mainline connection and the lateral liners' extent of coverage (length through the lateral). Among the various types of CIP liner, main and lateral cured-in-place liner (MLCIPL) provides effective rehabilitation of both mainline and lateral pipes. It also provides a solution for leaky mainline and lateral joints, which are the most critical points for I&I. By using MLCIPL in the lateral relining process, a resin-impregnated liner is positioned on a bladder so that when expanded, it will develop a circular liner within the sewer main. After transporting the bladder through the sewer main to the lateral pipe location, the liner is inserted tightly inside the lateral and into a full circle around the inside of the main sewer pipe with the application of inflation pressure (NASSCO, 2012). Figure 5-1 shows a MLCIPL liner, also known as a T-Liner according to LMK Technologies ("LMK Technologies," n.d.).

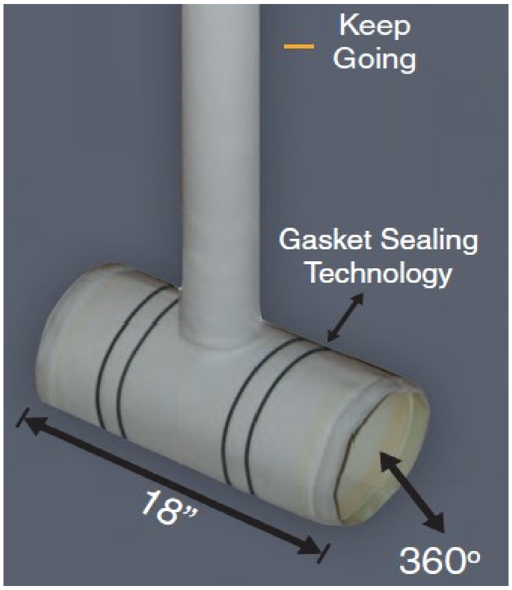


**Figure 5-1: T-Liner or MLCIPL ("LMK Technologies," n.d.)**

In this study, a productivity analysis of MLCIPL projects is performed using simulation by Simphony software. A simulation technique enables detailed construction processes to be modeled on a computer, supporting the decision making process by allowing managers to examine various options, compare their results, and select a near-optimal solution. Simulation is an excellent tool for project management as it has the capability to capture the uncertainties and risks of construction projects and develop alternative options for the stakeholders of the project in a very short period of time (Ruwanpura and Ariaratnam, 2007). One of the challenges of the construction planning stage is selecting an appropriate construction set-up, such as crew and equipment conformation, for a project. It is essential to choose a suitable method that can save costs, time, and avoid significant disruption in the area, especially for projects in urban settings. Management must consider possible resource combinations (crew and equipment), test various construction scenarios, calculate the associated cost and time for each scenario, and determine the most desirable solution. In this research, a simulation-based approach was used to assist decision makers in choosing the best crew and equipment combination for MLCIPL lateral relining process based on field data gathered from installation sites visited in Edmonton, Alberta, Canada.

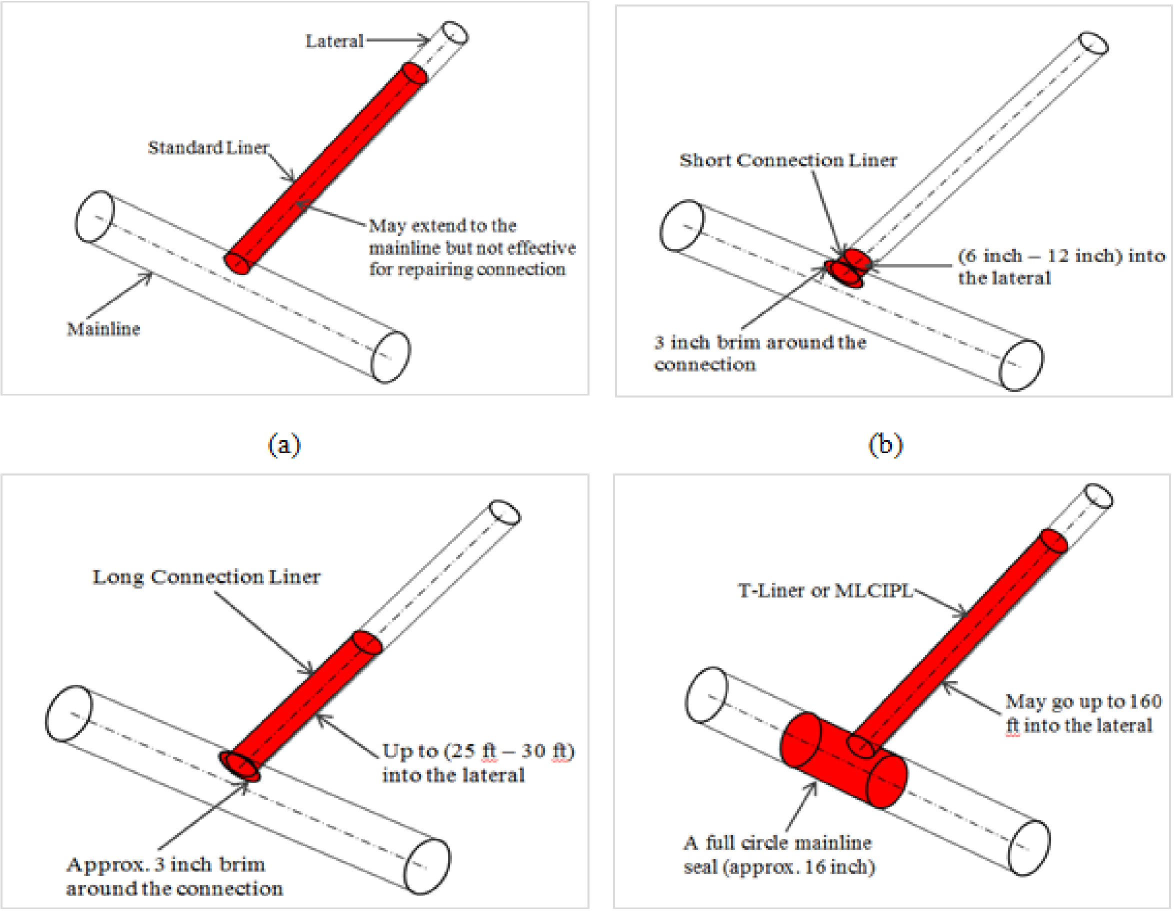
## 5.2 Objective and Methodology

The objective of this research is to show the application of Simphony simulation on the lateral relining process by MLCIPL and analyze the productivity of MLCIPL projects using different crew and equipment compositions. Modifications in the installation sequence are also suggested to improve the productivity, as shown in a modified model. Simulation results are considered reliable since the model is validated using field installation data.

With the purpose of investigating the productivity of MLCIPL projects, the lateral relining procedure was divided into different steps. In order to validate the model, a total of five MLCIPL projects' duration were collected on the field and the model results were compared to the field data. Since the simulation is validated and the result of the simulation model and that of the field data were in good agreement, the outcome of the simulation is expected to be reliable. Observation and investigation of the MLCIPL procedure have indicated that its productivity may be improved by modifying the sequence of the installation steps. The obtained results demonstrate a great enhancement in productivity.

## 5.3 Lateral Relining Process by MLCIPL

The CIP lining procedure involves using air inversion to insert a resin-impregnated fabric tube into an existing deteriorated lateral. The fabric used in these pipes is polyester felt or reinforced fiberglass. The liner is inserted through the inversion process, and steam or water is introduced to cure the pipe (Conway, 2008). For CIP lining, varieties of systems are on the market: they differ in the types of fabric, resins, and curing system. CIP lining can provide structural repair with negligible digging and minimum diameter reduction (Sterling et al., 2010). Simicevic and Sterling showed various types of CIP lateral liner (Figure 5-2), depending on the treatment of the lateral-mainline connection and the coverage length of lateral liners (Simicevic and Sterling, 2006b).



(a) (b) (c) (d)

**Figure 5-2: Different types of CIP lateral liner: (a) Standard Liner (b) Short Connection Liner (c) Long Connection Liner (d) T-Liner or MLCIPL. Modified and recreated from (Simicevic and Sterling, 2006b)**

Among the different types of CIP lateral liners the standard liner approach (Figure 5-2a) does not provide proper seal for the lateral/mainline connection. It is shaped like simple tubes and can be installed through cleanout or small pits. As the lateral/mainline connection is the most critical point at sewer lateral’s deepest location, various systems have been introduced to offer a seal for only the connection or seals of the connection, and a short section of lateral (Sterling et al., 2010). Short connection liners (Figure 5-2b) are similar to this system with a flange inside the mainline and a smaller section of liner extending into the lateral and are often referred to as a "top hat". They are installed from the mainline and only the leaked mainline-to-lateral connection is addressed by them where a brim of approximately 3 inch wide is created in the mainline around the connection and the connection extends a short distance (typically about 6 inch) into the lateral. Whereas, long connection liners (Figure 5-2c) are inverted remotely from the mainline (usually up to 25 to 30 feet into the lateral) that create a brim similar to short connection liners around the lateral connection in the mainline (Simicevic and Sterling, 2006b). Recently, these systems have been conjoined into a system (T-liner, Figure 5-2d) that consists of a full-circle liner (typically 12 to 16 in.) inside the main line and a full CIP lateral liner with extent of coverage up to 160 feet (50 m) into the lateral from the mainline connection (Sterling et al., 2010). This T-Liner is also known as main and lateral cured-in-place liner (MLCIPL) according to ASTM F2561 (ASTM, 2011).

In the lateral relining process by MLCIPL, the Lateral pipe is rehabilitated remotely from the main pipe and a lateral cleanout. The pipe renovation is achieved by the inversion and inflation of a resin-impregnated, single-piece lateral and main connection liner assembly. The liner assembly is pressed against the lined main pipe by inflation of a bladder and held under pressure until the thermo-set resin has cured. When cured, the liner extends over a predetermined length of the service lateral and the full circumference of the main pipe connection, forming a continuous, single-piece, tight fitting, corrosion-resistant, and verifiable non-leaking CIPP inclusive with gasket seals (Kiest Jr. and Gage, 2009). The materials and installation practices must follow the minimum requirements of ASTM F2561 (ASTM, 2011).

Pipe preparation, wetout, and relining are the three significant activities of the MLCIPL process. In the initial step of this process, all crew members and equipment are mobilized to the job site. After site access, proper equipment layout and traffic control operation, both the mainline and lateral should be properly cleaned. The mainline is flushed twice with a flusher nozzle by making forward and backward passes using a high-speed water jet from a flusher truck. With a robotic camera operated from a CCTV truck, the existing mainline must be CCTV-inspected after cleaning to check for debris, roots, damage, offset joints, or any other defect impeding proper installation. Simultaneously, the lateral is inspected with a pushing camera through the cleanout, and all roots and debris are cleaned using a mechanical cutting machine.

After cleaning, the lateral and main connection liner assembly is prepared according to proper measurements. Lateral and main connection liner assembly, also called liner-bladder assembly, is where the mainline fabric sheet is wrapped circumferentially around the main section of the bladder so one end overlaps the second end. The mainline fabric sheet is sized so as to create a circular liner of equal size to the inner diameter of the mainline pipe when the main bladder is expanded. The lateral bladder and fabric liner tube are continuous in length. After the preparation of liner-bladder assembly, the MLCIPL process moves forward with resin-impregnation, which is referred to as the wetout process. To avoid the resin cooking, tube and sheet preparation and resin saturation normally take place in the controlled environment of a wetout trailer on the job site where the resin and tube temperatures are regulated. During resin impregnation, air must first be evacuated to create conditions for vacuum impregnation, and then the catalyzed resin is introduced into the tube under vacuum conditions. This way, the air is completely displaced with resin while the resin saturates the lateral and main connection liner assembly.

During the relining step, the resin-saturated liner-bladder assembly (Figure 5-3) is inserted into the launcher and lay flat hose. The launcher is a rigid, elongated tube with an aperture located in its centre and a high-temperature, abrasion-resistant lay flat launch hose attached to one end. The main bladder is attached to the launcher tube at each of its ends by banding methods and the fabric sheet is wrapped around the main bladder, whereas the lateral liner-bladder assembly portion is drawn inside the lay flat hose. Before inserting the launcher in a mainline manhole, a robotic camera is connected with the launcher. The robotic camera is controlled from the CCTV truck to pull the connected launcher with the liner-bladder assembly and lay flat hose through the mainline into the proper position of lateral. A pushing camera in the main-to-lateral joint should also be present through the lateral cleanout to give proper direction to the CCTV controller.

**Figure 5-3: Resin-impregnated lateral and main connection liner-bladder assembly prior to inserting into the mainline manhole (Courtesy: Installation by IVIS Inc.).**

Once the launcher with the liner-bladder assembly is in exact position of the lateral to be relined, the air inversion process initiates. Air is introduced from a boiler truck to create the proper installation pressure. The liner-bladder assembly inflates when it is pressurized, causing the mainline resin-saturated fabric sheets to expand and press tightly against the mainline pipe wall. Simultaneously, the lateral bladder and wetout fabric liner invert up into the sewer service pipe. After installation, the installed liner-bladder assembly is cured using steam. In the initial step of the curing process, the installed liner-bladder assembly is heated up to proper curing temperature and cooked for a defined time. After proper curing, steam introduction is stopped and the cooling down begins. Finally, the bladder is pulled back to the lay flat hose using the inversion rope and, with the help of the boiler truck, the launcher with the lay flat hose is reverted to the manhole.

After equipment removal, the pushing camera is used through the lateral cleanout for post-inspection to verify the MLCIPL installation. The installed MLCIPL should be free of dry spots, lifts, and delamination.

## 5.4 Special Purpose Simulation (SPS) for Lateral Relining

This research developed simulation models in Simphony.NET 4.0, a Microsoft Windows-based construction simulation tool to model discrete event simulation systems. This software is the latest version of Simphony; it was originally developed under the guidance of the Natural Sciences and Engineering Research Council (NSERC) and the Alberta Construction Industry Research Chair Program in Construction Engineering and Management (Vaseli, 2015; Hajjar and AbouRizk, 2000). Simphony offers a background for developing General Purpose Simulation (GPS) and Special Purpose Simulation (SPS) templates (Moghani et al., 2011). A SPS template is a collection of modelling elements designed to have a behaviour customizable to a specific process; these elements usually have icons that resemble the real-world systems they represent. On the other hand, a GPS template is a collection of high-level elements that do not necessarily resemble a real-world system. Using the GPS template, users build models utilizing abstract elements such as activities, queues, and resources. SPS templates, however, provide a set of elements related to a particular construction domain, which makes simulation more accessible for industry (Moghani et al., 2011). In this study, a Simphony SPS template was used to develop the model. Simphony has a graphical user interface and hierarchical modeling capability. Users can drag and drop elements into the Simphony modeling interface and connect them based on the logic of a given process. Resources are assigned for diverse activities in the process, and statistical results are available for every resource in the process after the simulation runs (Moghani et al., 2011).

In Simphony, a simulation model can have any number of runs for Monte Carlo simulation purposes if required. More than one scenario can be modeled in one simulation file, thus allowing users to run scenarios and compare them simultaneously. Simphony includes statistical outputs and different kinds of reports, such as cost and resource utilization, which are useful for project management (Moghani et al., 2011). Simphony is regarded as an appropriate tool for integration of simulation into a construction management procedure (Vaseli, 2015; AbouRizk et al., 1999; Lueke et al., 1999). Trenchless construction processes are excellent candidates for the application of computer simulation (Ruwanpura and Ariaratnam, 2007).

A SPS model was developed to estimate the MLCIPL projects' duration and productivity and, specifically, to investigate the impact of crew and equipment composition on the process productivity. In Simphony, entity is one of the most significant modeling features that represents material, resource or finished product. In this model, an entity is considered as one MLCIPL project.

In order to develop the model, the MLCIPL lateral relining process was divided into different activities. Remarkably, the duration of each step and labour productivity diverges depending on different factors such as weather condition, employees' proficiency level and type of equipment. To consider all these aspects, the durations are presented as minimum, maximum, and most likely values (i.e., a triangular distribution) for each activity based on installation site visits. An exception was made for mainline flushing and sending robotic cameras from one manhole to another because duration of these two activities depend on mainline length from manhole to manhole (MH-MH). In this study, the mainline lengths (MH-MH) of different neighborhoods in the City of Edmonton have been fitted into a beta distribution (Figure 5-4) by using Oracle Crystal Ball software. Simphony can generate different durations in different runs by using that distribution, flusher nozzle speed, and robotic camera crawling speed.

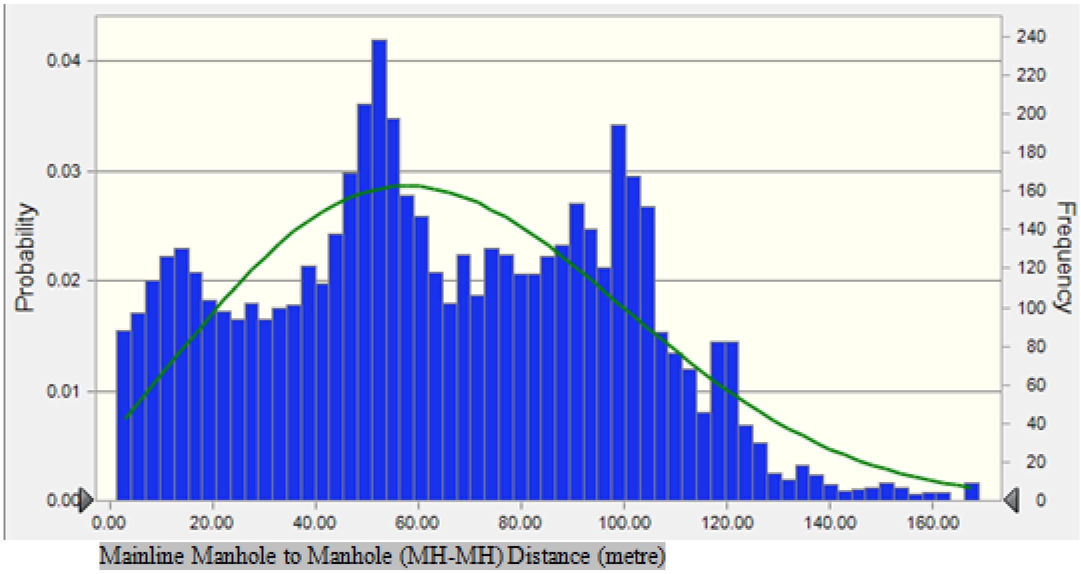


**Figure 5-4: Fitted beta distribution of mainline MH-MH length for different neighbourhood in Edmonton**

The model was developed with regards to different activities and corresponding resources assigned to them, as shown in Table 5-1. The crew size is considered to be the resource; the boiler truck, CCTV truck and flusher truck are considered to be the equipment. The flusher truck is utilized during mainline flushing activity only. The CCTV truck, on the other hand, is used for robotic camera operation. It also directs and pulls the launcher with liner-bladder assembly into proper position within the pipe and used until liner inversion. The boiler truck is utilized for liner-bladder assembly inversion, curing steps, and bladder and launcher reverting activities.

**Table 5-1: Time distribution parameters, based on MLCIPL installation site visit**

| Activity | Minimum (min) | Most Likely (min) | Maximum (min) | Number of Labour Assigned |
|---|---|---|---|---|
| Mobilization | 25 | 30 | 50 | 4 |
| Traffic control, layout and equipment setup | 10 | 15 | 20 | 4 |
| Flushing the mainline | Depends on MH-MH length distribution | | | 1 |
| Sending robotic camera from MH-MH | Depends on MH-MH length distribution | | | 1 |
| CCTV by pushing camera | 10 | 15 | 25 | 1 |
| Lateral cleaning | 25 | 30 | 40 | 1 |
| Launcher setup and measurement | 10 | 20 | 25 | 4 |
| Preparation of liner-bladder assembly | 10 | 15 | 20 | 2 |
| Resin preparation | 25 | 27 | 30 | 1 |
| Resin impregnation | 10 | 13 | 13 | 3 |
| Insertion of liner-bladder assembly into launcher and lay flat hose | 10 | 15 | 22 | 4 |
| Taking launcher to the right position in mainline–to-lateral joint | 25 | 30 | 36 | 4 |
| Inversion of liner-bladder assembly | 5 | 7 | 10 | 4 |
| Heating by steam | 20 | 25 | 30 | 1 |
| Curing | 28 | 30 | 40 | 1 |
| Cooling down | 4 | 5 | 6 | 1 |
| Reverting bladder | 5 | 7 | 10 | 3 |
| Taking out launcher and lay flat hose from mainline | 7 | 10 | 15 | 3 |

| | | | | |
|---|---|---|---|---|
| Disconnecting lay flat hose and bladder from launcher | 5 | 10 | 15 | 3 |
| Post-inspection CCTV by pushing camera | 5 | 10 | 15 | 1 |
| Wrap up | 4 | 5 | 7 | 4 |

Figure 5-5 illustrates the basic simulation model used for the MLCIPL productivity analysis and indicates the steps and assigned resources. Empty squares symbolize each task in the lateral relining process; squares with a human symbol and a plus sign signify assigning the resource, while a minus sign represents the resource release.

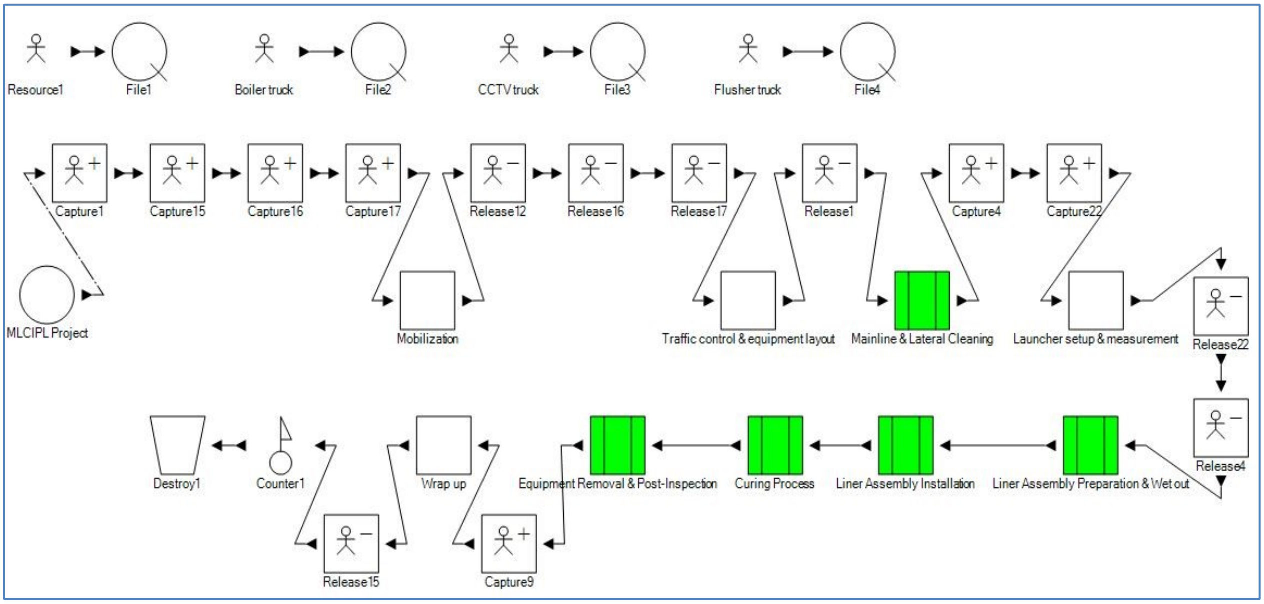
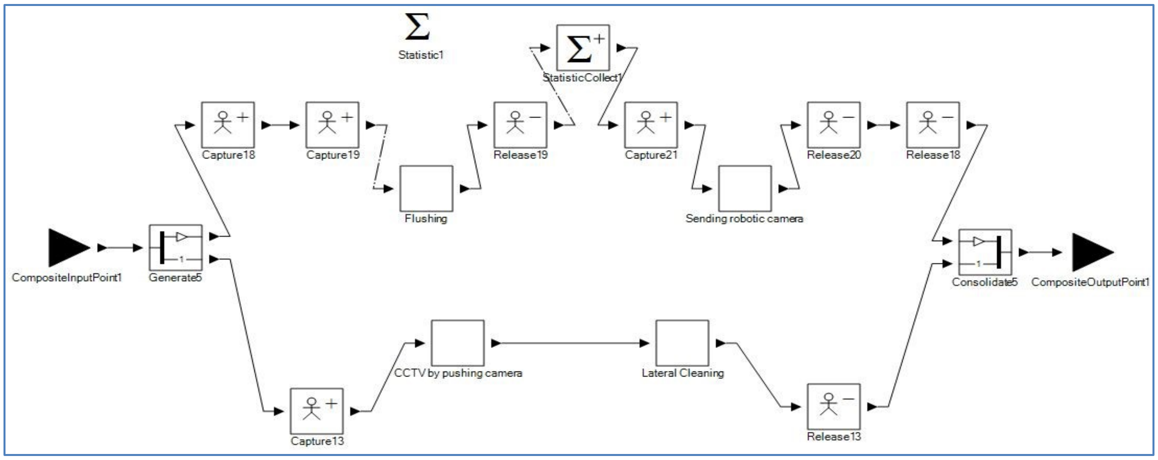
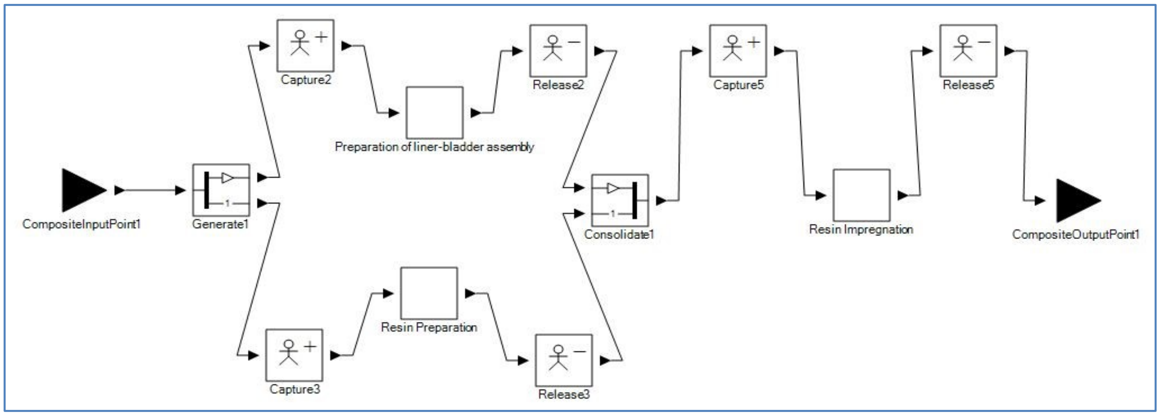


**Figure 5-5: Basic simulation model for MLCIPL process**

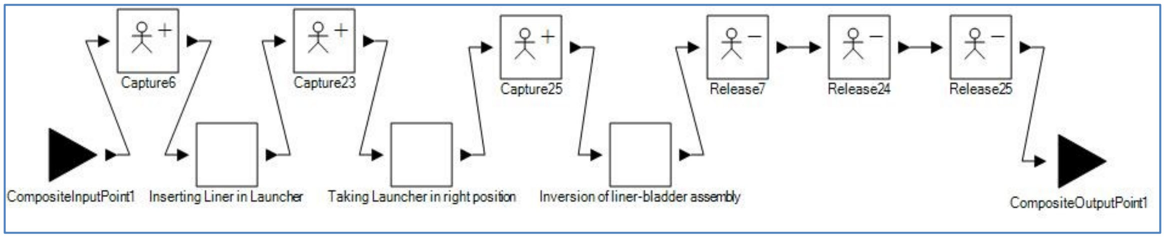
In order to make the model more organized and understandable for the user, all details for the mainline and lateral cleaning, liner assembly preparation, wetout and installation, curing process, equipment removal, and post-inspection are encapsulated in five composite elements (i.e., an element that has no simulation behaviour and is used for grouping elements), shown as green rectangular elements in the basic model (Figure 5-5). Detailed procedures of different activities in the basic model, including composite elements, were previously discussed in the lateral relining procedure by MLCIPL in Section 5.3. All the features of composite elements are illustrated in Figure 5-6.


Statistic1
StatisticCollect1
Capture18
Capture19
Release19
Capture21
Release20
Release18
Flushing
Sending robotic camera
CompositeInputPoint1
Generate5
Consolidate5
CompositeOutputPoint1
CCTV by pushing camera
Lateral Cleaning
Capture13
Release13

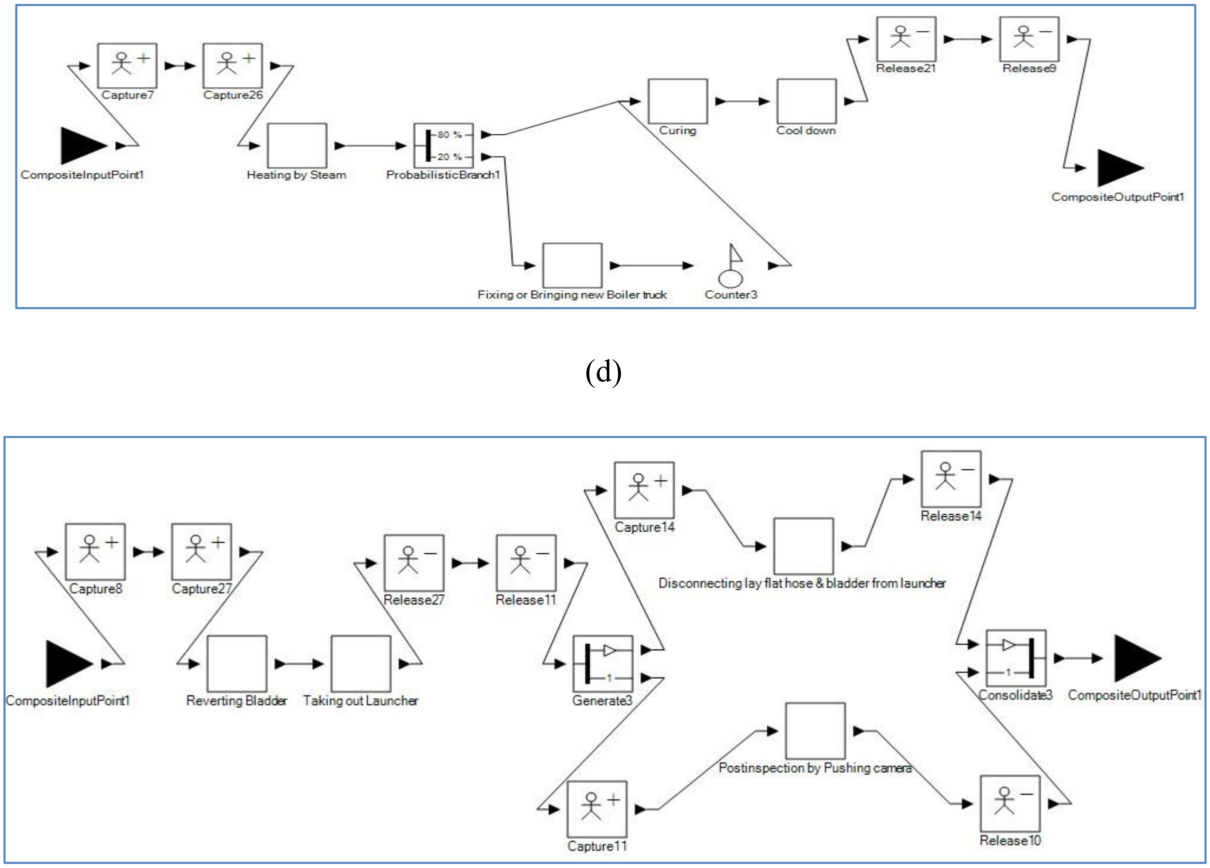
(a)


Capture2
Release2
Capture5
Release5
Preparation of liner-bladder assembly
CompositeInputPoint1
Generate1
Consolidate1
Resin Impregnation
CompositeOutputPoint1
Resin Preparation
Capture3
Release3

(b)


Capture6
Capture23
Capture25
Release7
Release24
Release25
CompositeInputPoint1
Inserting Liner in Launcher
Taking Launcher in right position
Inversion of liner-bladder assembly
CompositeOutputPoint1

(c)



(d)

(e)

**Figure 5-6: Details of simulation model for composite elements: (a) Mainline and lateral cleaning; (b) Liner assembly preparation and wetout; (c) Liner assembly installation; (d) Curing process; and (e) Equipment removal and post-inspection**

## 5.5 Simulation Validation

In this study, model validation is achieved by comparing the simulation results to actual field installation data, as presented in Table 5-2.

**Table 5-2: MLCIPL project duration comparison for model validation**

| Description | Simulation Result (hr) | Field Installation Result (hr) | Percentage Error (%) |
|---|---|---|---|
| Duration of 1st MLCIPL project | 4.76 | 4.35 | 9.42 |
| Duration of 2nd MLCIPL project | 4.68 | 4.30 | 8.84 |
| Duration of 3rd MLCIPL project | 5.02 | 4.90 | 2.45 |

|  |  |  |  |
|---|---|---|---|
| Duration of 4th MLCIPL project | 4.82 | 4.40 | 9.55 |
| Duration of 5th MLCIPL project | 5.11 | 4.75 | 7.58 |

Because the error between the simulation results and field installation duration is less than 10% for each MLCIPL installation, the simulation results may be considered reliable. These differences may be caused by workers' efficiency levels, surrounding weather conditions and different lengths of mainline MH-MH distribution systems.

## 5.6 Productivity Analysis

Construction productivity has a significant role in project success as high productivity results in lower unit cost per task or operation. Productivity is generally defined as the ratio of produced output to unit of resource input, such as labour, energy, raw material etc. Considering the resources used, typical productivity ratios are: a.) the total factor productivity or multi-factor productivity, in which the output is with regard to all used resources; and b.) labour productivity, in which the output is correlated to only labour (Vasely, 2015). Labour is signified by the employed persons, working hours, or labour cost to analyse labour productivity (Vasely, 2015; O'Grady, 2014). Typically, keeping track of labour productivity with respect to time provides constructive information to investigate and assess the efficiency of the projects and permits managers to move toward saving costs and enhancing performance (Vasely, 2015; Su, 2010). In the construction industry, resource input is represented as the required amount of time to accomplish one unit of output. While, output unit is selected according to the objective of productivity investigation. In this study, the output unit is one MLCIPL project.

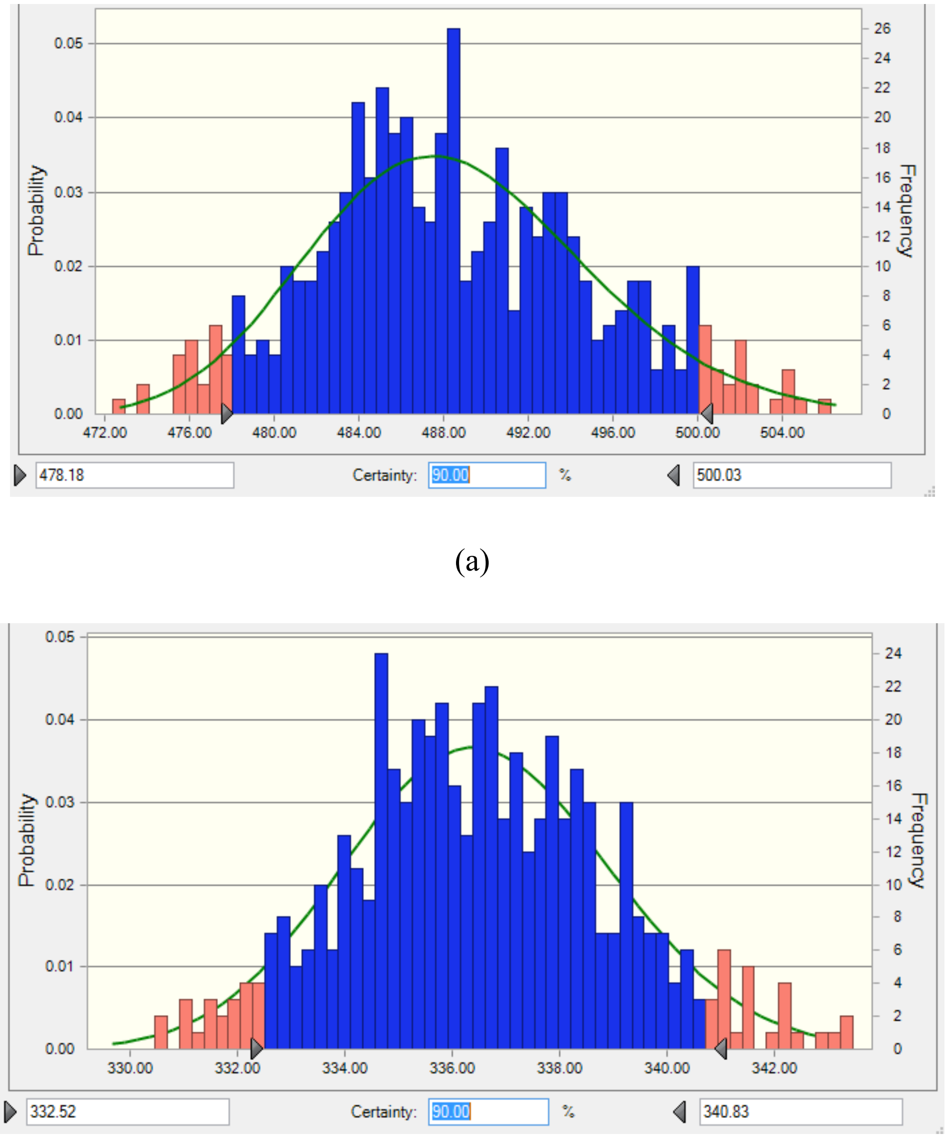
A contract in the City of Edmonton consisting of 100 MLCIPL projects was used as the data pool for performing the productivity analysis. The simulation model was executed for 500 runs to perform Monte Carlo simulation analysis and to provide users with statistical output such as resource utilization and total duration. Also, for every simulation model, different scenarios were defined by changing inputs such as crew and equipment compositions. This allows users to test possible situations, compare outputs, and select the best solution. As an example, the results for different scenarios are included in Table 5-3. A 20% probability of boiler truck breakdown, according to an expert's opinion based on industry observation, was also considered during the curing process operation, which makes the model more realistic for application on the field.

**Table 5-3: Simulation results for different crew and equipment compositions**

| Equipment composition: 1 boiler truck, 1 CCTV truck and 1 flusher truck | | | |
|---|---|---|---|
| Crew Size | Total duration (hr) | Required man-hour (mhr) | Productivity (project/mhr) |
| 4 | 488.58 | 1954.32 | 0.051169 |
| 5 | 400.44 | 2002.20 | 0.049945 |
| 6 | 373.01 | 2238.06 | 0.044682 |
| 7 | 328.81 | 2301.67 | 0.043447 |
| 8 | 285.59 | 2284.72 | 0.043769 |
| **Equipment composition: 2 boiler trucks, 2 CCTV trucks and 1 flusher truck** | | | |
| Crew Size | Total duration (hr) | Required man-hour (mhr) | Productivity (project/mhr) |
| 5 | 336.47 | 1682.35 | 0.059441 |
| 6 | 298.03 | 1788.18 | 0.055923 |
| 7 | 259.28 | 1814.96 | 0.055098 |
| 8 | 219.07 | 1752.56 | 0.057059 |
| **Equipment composition: 2 boiler trucks, 1 CCTV truck and 1 flusher truck** | | | |
| Crew Size | Total duration (hr) | Required man-hour (mhr) | Productivity (project/mhr) |
| 4 | 455.62 | 1822.48 | 0.054870 |
| 5 | 336.70 | 1683.50 | 0.059400 |
| 6 | 299.31 | 1795.86 | 0.055684 |
| 7 | 265.02 | 1855.14 | 0.053904 |
| 8 | 235.00 | 1880.00 | 0.053191 |

During the MLCIPL installation site visit, it was found that minimum crew size required to complete a MLCIPL project was consisted of four labours and minimum required equipment were one boiler, CCTV and flusher truck. This model was followed in order to find some bottlenecks in the process. For example, during the curing process operation, only one labourer is required but another three labourers are waiting in the resource file for a significant time; this was a major bottleneck. In this case, if the crew size is increased in the model, then the labourers waiting in the resource file, together with the increased labour, can start another simultaneous MLCIPL project. This is applicable for not only the curing process, but also for other activities, provided all equipment is available. According to Table 3, by using one boiler, CCTV and flusher truck, and with respect to an increase in crew size, all projects can be accomplished in a shorter time. However, the required increase in man-hours then reduces productivity because of the lack of availability of equipment. The resource utilization simulation result shows that for a crew size of four, the percent utilization of boiler, CCTV and flusher truck is 48.4%, 34.2% and 18.3%, respectively. As the flusher truck is used only for flushing activity, it has the lowest percent of usage, so more boiler and CCTV trucks can be introduced in the model without changing the flusher truck. From Table 3, it is obvious that if one boiler and CCTV truck are increased, then the total project duration is shortened and productivity is higher than it was previously. Table 3 also shows that by changing the equipment composition, a crew size of five offers the best productivity and lowest man-hour cost. Furthermore, all parameters (duration, man-hour and productivity) are almost the same if they are increased by one boiler and CCTV truck or one boiler truck only. Finally, it can be concluded from Table 3 that the best economic option to get the highest productivity for MLCIPL projects is a crew size of five using two boiler, one CCTV and one flusher truck. As in this case, the cost of one CCTV truck can be saved in compared to option of utilizing two boiler and CCTV and one flusher truck with crew size of five. Based on contract duration, assumptions for the equipment list, and number of crew available, decision makers should choose which alternative would be the best solution according to cost and duration.

The Simphony model also provides statistical results for the total duration of MLCIPL projects considered; since 500 runs were considered for each model, the statistical results contained a range of numbers with a minimum, maximum and mean value of the range. Figure 5-7 demonstrates the total time distribution of MLCIPL projects, where the X-axis represents the total duration to complete 100 MLCIPL projects and the Y-axis represents the probability and frequency of that duration. These graphs are obtained using the simulation results with 500 iteration and appropriate distribution functions are fitted to probability bar charts using Oracle Crystal Ball software. With a certainty level of 90%, the total duration to complete 100 MLCIPL projects is between 478 to 500 hours by using a crew size of four and one boiler, CCTV and flusher truck. On the other hand, with a crew size of five and one more boiler truck, these values are approximately 332 to 340 hours.



(a)

(b)

**Figure 5-7: Probabilistic gamma distribution of total duration to complete 100 MLCIPL projects: (a) four crew members with one boiler, CCTV and flusher truck; (b) five crew members with two boiler trucks and one CCTV and flusher truck**

## 5.7 Productivity Improvement

In the field installations, it was observed that after relining a service lateral from mainline MH-MH by MLCIPL, the crew would go to another nearby lateral in a different mainline MH-MH distribution to perform the installation. This scenario is ideal if there is only a single service lateral to reline in the mainline MH-MH length. However, in real scenarios, there may be multiple service laterals to reline in a single mainline MH-MH length. During the field visit, it was seen that the crew did not install multiple service laterals in a single mainline MH-MH length consecutively. Rather, they relined in a different service lateral located in a different mainline MH-MH nearby.

This study introduces a new sequence of steps for relining multiple service laterals in a single mainline MH-MH length distribution system using MLCIPL. For this type of distribution system, it is better to reline the multiple service laterals in such a way that after fully accomplishing the MLCIPL installation in one lateral, the crew can use the previous setup to initiate the relining process in another lateral in the same mainline MH-MH length. The main advantage is that for the MLCIPL installation of new service laterals after relining the first lateral, some initial activities (e.g. mobilization, traffic control, equipment set up, mainline flushing, measurement) are not required. The project is therefore more productive and cost-effective because of time saved in project duration and equipment operation.

To investigate and compare the effect of the new approach for multiple service laterals in a single mainline MH-MH length, in the previous contract of 100 MLCIPL projects in Section 5.6, 30% of the laterals are considered to be part of the multiple service laterals in a single mainline MH-MH, and the remaining 70% of the laterals are part of the only single service lateral in a mainline MH-MH distribution. Figure 5-8 shows the new simulated model by considering 30% of the laterals to be part of the multiple service laterals in a single mainline MH-MH distribution.

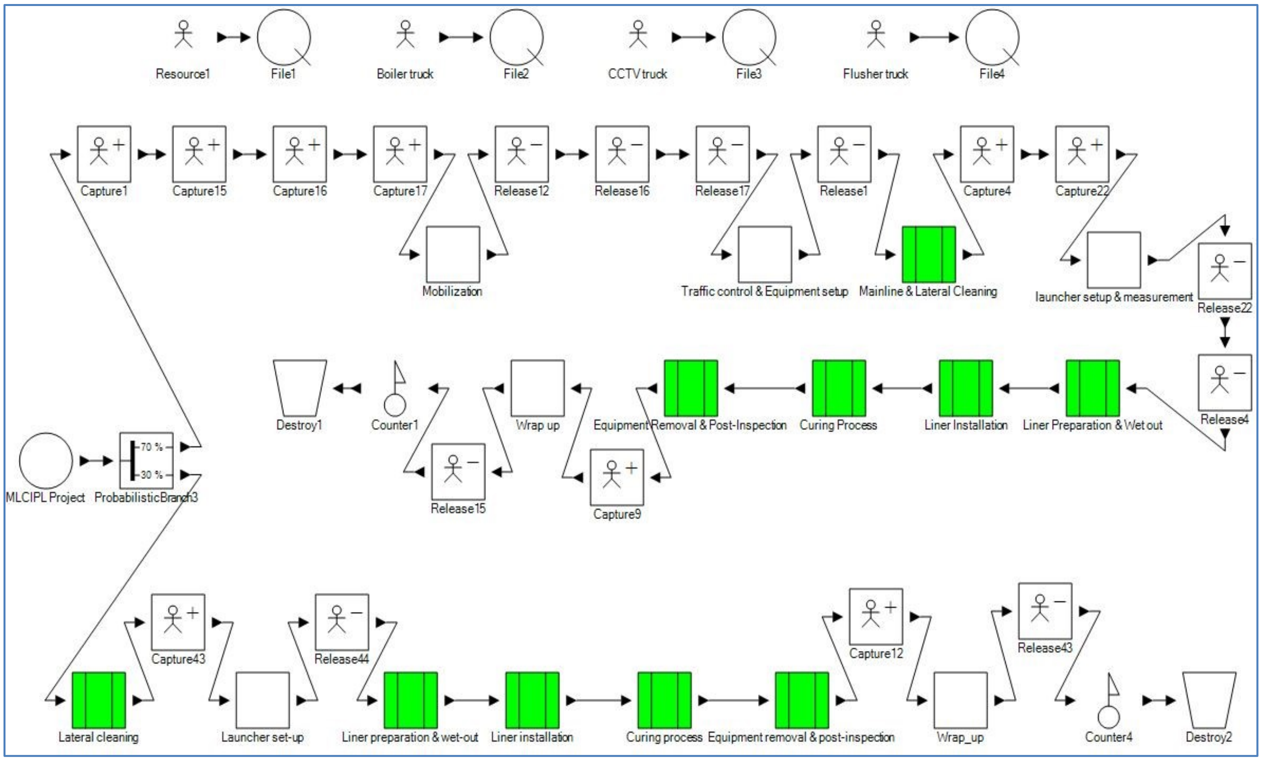


**Figure 5-8: Modified simulation model to improve MLCIPL project productivity**

Table 5-4 shows the simulation result by considering a crew size of four for a total of 100 MLCIPL projects. If multiple laterals are relined by considering the proposed strategy above, then it is estimated that the contract of 100 MLCIPL projects can be completed in a shorter time and the required man-hours are also lower than previously, resulting in significant cost savings. New relining procedures of multiple laterals result in approximately 18.22% increase in productivity.

**Table 5-4: Simulation result from modified model**

| Description | Total Duration (hr) | Required Man-hour (mhr) | Productivity (project/mhr) |
|---|---|---|---|
| Multiple laterals not considered | 488.58 | 1954.32 | 0.051169 |
| 30% multiple laterals considered | 413.26 | 1653.04 | 0.060495 |

## 5.8 Conclusions

This research explores applying simulation modelling to select the proper compositions of crew and equipment for lateral relining projects using main and lateral cured-in place liner (MLCIPL). Simulation is a dominant tool in project management; it can help managements choose the optimum construction scenario while considering limitations and uncertainty of time, money, labourers and equipment. This research utilizes the Special Purpose Simulation (SPS) template in Simphony.NET 4.0 to develop models for MLCIPL projects based on actual installation site visits.

This SPS can be utilized to predict the project duration. In addition, it enables to operate "What-if" scenarios to the developed simulation model. Therefore, the efficacy of any amendment for the installation practice can first be validated by the model prior to executing in the real project. This model can estimate the project duration with respect to different crew and equipment compositions. Based on the simulation results in the basic model, a crew size consisting of five labourers with two boiler trucks, one flusher and one CCTV truck gives the highest productivity and lowest estimated labour costs to complete 100 MLCIPL projects.

In this study, an altered model was also provided by considering a modified construction sequence with multiple service laterals in a single mainline MH-MH distribution. Using the modified model, the productivity of MLCIPL projects can be increased. In the example shown in this study, the productivity can be increased by approximately 18% if 30% of the total service laterals are considered part of the multiple laterals in the distribution system.

# Chapter 6: Summary and Conclusions

This chapter summarizes the main conclusions of the thesis and finishes by highlighting areas for future research.

## 6.1 Summary

Cured-in-place pipe (CIPP) is one of the most versatile trenchless rehabilitation methods to revitalize aging and deteriorating underground infrastructure. Although the use of CIPP is rapidly increasing, various types of pipe defects and complexity of the CIPP process leads to a number of issues and challenges that may arise during CIPP installation work. This thesis provides a systematic review on the issues and challenges associated with CIPP rehabilitation projects of sewer mains, water mains and service laterals. In addition, this study discusses relevant measures adopted in current practices to mitigate these challenges. This attempt was made to benefit trenchless CIPP companies and water distribution and wastewater municipality sectors.

Productivity is crucial information for resource planning, progress tracking, and budget control. Construction productivity plays an important role in the project success; high productivity results in lower unit cost to perform a task. Therefore, it is necessary to analyze CIPP productivity, which can be influenced by pipe diameter and liner thickness. The results of this study will contribute to more accurate estimations of CIPP project productivity, thereby helping with effective CIPP rehabilitation project planning and management.

Furthermore, the concept of special purpose simulation by Simphony was selected for the first time to be implemented in lateral relining process by main and lateral cured-in-place liner (MLCIPL) to select appropriate construction set-up such as crew and equipment conformation. Using the time distributions of different activities in MLCIPL projects obtained from the installation site visit enabled the development of a discrete event simulation tool to model the lateral CIPP rehabilitation process. The tool enables users to create simulation models for different resource compositions and estimate resource utilization, total duration of the project and construction productivity. In addition, the lateral CIPP relining procedure was modified in a way to achieve improvement in the productivity. Productivity enhancement was shown using the modified model outcome that results in less production costs and helps contractors provide more cost-effective operations to municipalities.

## 6.2 Conclusions

As the nation's infrastructure continues to deteriorate, the use of CIPP rehabilitation technology becomes more attractive. However, relining using CIPP may be accompanied by a number of issues and challenges; hence, many potential advancements in the application of CIPP technology remain. This study provides a systematic review and comprehensive summary of information needed by researchers and engineers to understand challenges that may arise during CIPP installation work. In this research, the challenges that may occur in a water and wastewater infrastructure CIPP project have been divided into five different categories.

In addition, this study describes the CIPP process and conducts a productivity analysis of more than 40 sewer mainlines in Edmonton, Alberta, rehabilitated through CIPP inversion process. The time and number of crew members required for different steps in the CIPP process have been tracked to determine productivity. For the productivity analysis, the CIPP process has been divided into three significant activities (pipe preparation/prep, wetout and relining), and the selected pipe size varies from 375 mm to 600 mm and installed liner thickness is from 7.5 mm to 12 mm. Collected data from large diameter CIPP liner installations in different neighborhoods in Edmonton, Alberta, revealed that:

- During prep operations, all heavy roots, debris, encrustations, and protruding laterals are cut with either a flusher nozzle or a remote-controlled robotic cutter crawler attached to the CCTV camera. Of the two methods, the flusher nozzle is two times more productive. However, the cutter crawler offers its operator increased control, particularity in cutting protruding PVC.
- As pipe size increases, average prep productivity decreases due to greater time requirements for prep completion. Generally, larger pipe is associated with higher prep time due to thicker encrustation that requires greater cutting time.
- A significant variation exists between the maximum and minimum prep productivity values associated with each pipe diameter. The most significant factor for variations in the prep productivity value is the pipe condition and number of service connections.

Generally, the more debris, roots, damage, offset joints, and service connection problems, the more time it takes to complete prep operation.

- During the wetout process, smaller diameter tubes have a higher associated productivity rate than larger ones. For instance, the wetout crew should anticipate about three times more required time to accomplish the wetout process for a 600-mm diameter tube than a 375-mm diameter tube.
- Relining is the most significant step of the CIPP process. Among the different activities in the relining process, the curing step represents a significant portion of time that is more than 50% of the total time required for the entire relining process.
- An increase in pipe diameter decreases curing production. Moreover, for each particular pipe diameter, higher liner thickness is associated with a lower production rate (i.e. increased amount of time required to complete the process).

In this research, a simulation-based approach was used to assist decision makers in choosing the best crew and equipment combinations for lateral rehabilitation using CIPP from the mainline, also known as lateral relining process by using main and lateral cured-in-place liner (MLCIPL). Simulation models were developed in Simphony.NET 4.0, a Microsoft Windows-based construction simulation tool to model discrete event simulation systems. A contract in the City of Edmonton consisting of 100 MLCIPL projects was used as a data pool for performing the productivity analysis. The simulation model performs Monte Carlo simulation analysis and provides users with statistical output such as resource utilization and total duration, and it was observed that:

- Special Purpose Simulation (SPS) can be used for estimating the project duration. "What-if" scenarios can also be applied to the developed simulation model, so the effectiveness of any modification for the installation procedure can first be verified by the model before implementing any changes to the project.
- By comparing different scenarios, it was evident that a crew size of five utilizing two boiler trucks, one CCTV and one flusher truck is the best economic option to get the highest productivity for MLCIPL projects.
- From the statistical results of the Simphony model and with a certainty level of 90%, the total duration to complete 100 MLCIPL projects is between 478 to 500 hours by using a

crew size of four and one boiler, CCTV and flusher truck. On the other hand, with a crew size of five and one more boiler truck, these values are approximately 332 to 340 hours.

- Furthermore, to enhance productivity, an altered model has been provided by considering a modified construction sequence in the case of multiple service laterals in a single mainline MH-MH distribution. For instance, the productivity can be increased by approximately 18% if 30% of the total service laterals are considered part of multiple laterals in the distribution system.

## 6.3 Future Research

In case of sewer main CIPP installation projects, this research provides productivity results of large diameter (375 mm to 600 mm) pipes installed by air inversion and steam curing only. Therefore, it is recommended to consider collecting further data for a wide variety of pipe diameters, CIPP installation by pulled-in-place method and curing process initiated by hot water. This will lead to more effective productivity results for different scenarios and will allow engineers and contractors to update processes, increase construction efficiencies, and heighten the degree of accuracy in their cost and scheduling estimates. Also, together with pipe diameter and liner thickness, it would be helpful to analyze other productivity factors such as workers' experience and environmental factors for a cold region like Alberta.

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