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A comprehensive review on the challenges of cured-in-place pipe (CIPP) installations

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ABSTRACT

This paper outlines the issues and challenges associated with cured-in-place pipe (CIPP) rehabilitation projects of sewer mains, water mains, and service laterals. Common problems and challenges are first reviewed from the 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 paper discusses relevant measures adopted in the current practices to mitigate these challenges. The main purpose of this paper is to provide 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. Meanwhile, much effort is made to identify future research needed to better understand how the current practice deals with such issues and to find better solutions to current challenges.

Key words | CIPP, issues and challenges, service laterals, sewer main, trenchless, water main

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INTRODUCTION

A large proportion 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, which can be costly and disruptive to the surrounding environment, particularly in highly populated areas and problematic ground and site conditions. In contrast, 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 such as uncured linings must be fixed using spot repair or a full removal and replacement of the liner, causing a significant cost impact. As a result, CIPP industries and municipalities are constantly concerned about probable issues in any relining project. Sterling

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(2010) 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. Later, Selvakumar & Tafuri (2012) 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. In addition, Selvakumar *et al.* (2012) 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. However, the literature provides limited information on issues and complications encountered during CIPP rehabilitation processes. This paper provides a review of the obstacles and risks faced in CIPP projects, and those challenges have been 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.

OBJECTIVE AND METHODOLOGY

This paper presents key issues and challenges encountered during CIPP installation projects of sewer mains, water mains, and service laterals. The objective of this paper is to present a 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. Information used in this paper 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 providers, also produced a proportion of the information. The approach taken (literature review, industry information, and site visits) is intended to provide a comprehensive overview of the topic.

CATEGORIES OF ISSUES AND CHALLENGES

After an extensive literature 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.

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.

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 & Tafuri 2012). For sewer infrastructures, challenges can typically be related to cracks, severe internal corrosion (especially for concrete sewers), root intrusion, grease build-up together with sediment and debris, joint misalignment, excessive pipe deflection, separation and/or leakage, lateral connection leakage, and grade and alignment (Murray 2009; Selvakumar & Tafuri 2012). Pipe preparation or cleaning is the preliminary step for CIPP installation. Figure 1 shows some examples of pipe defects inside a sewer mainline.

The conditions mentioned above make the cleaning phase a significant challenge given that the state of the pipe might obstruct the operation of the equipment used, such as high speed water flushers, mechanical and/or robotic cutters, and closed-circuit television (CCTV). Moreover, CIPP installation in sewers with large radius curvature or flat surfaces, such as horseshoe-shaped sewers, egg-shaped sewers, and non-circular sections in general, exhibit special design challenges (Abraham & Gillani 1999; Seeta *et al.* 2009; Lucie *et al.* 2014). Broken and missing pipe, blockage due to debris and encrustation, and a

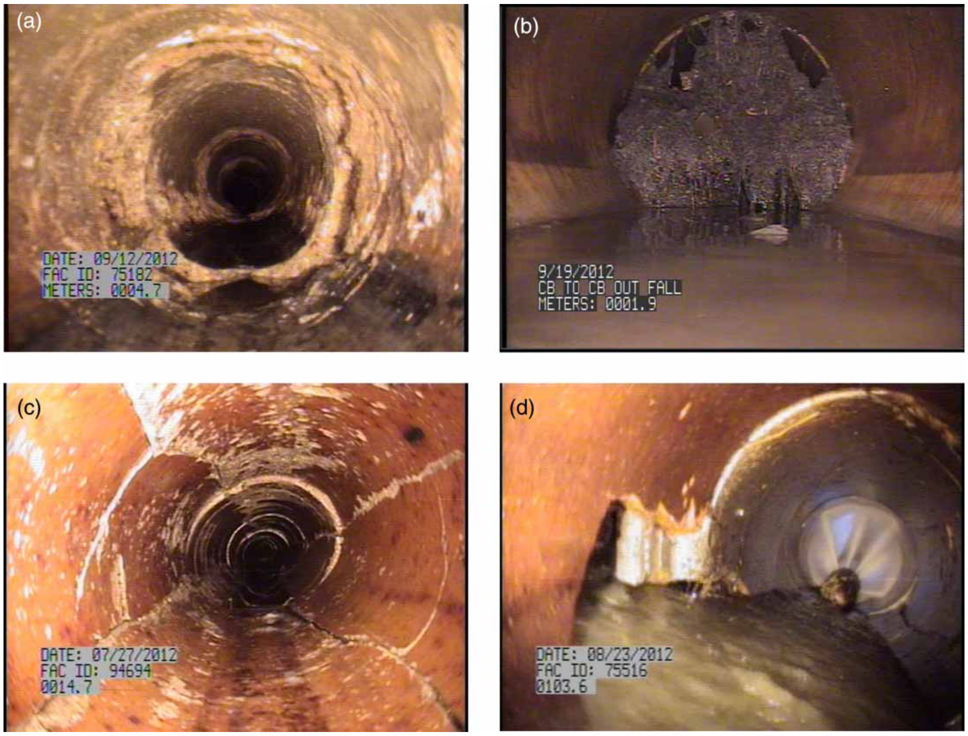

Figure 1 | Pipe defects inside a sewer mainline: (a) hole in pipe; (b) roots mass; (c) deformed pipe, multiple fractures, surface damage; (d) broken pipe with pieces missing (with permission from Navab 2014).

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 & Rodenberger 2011).

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, 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 & Tafuri 2012). In addition, pipe preparation and cleaning of water mains for CIPP installation may be difficult because of corrosion and thick encrustations. Over time, corrosion deposits build up on the inside walls of unlined pipes, resulting in tuberculation (Wassam 2015). Tuberculation and protruding service fittings are two special problems in water mains for which cleaning may not be possible, and the corresponding main segments may 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 & Coté 2015).

Lateral

According to the United States Census Bureau, there are over 76 million sewer laterals in the USA alone. Because of the abundant number of service laterals, lateral CIPP rehabilitation represents a significant and largely unmet societal cost liability. In addition, legal jurisdiction and private ownership issues aggravate this problem (Kristel *et al.* 2009). Even within one metropolitan area, the sewer laterals' ownership may differ significantly for municipalities (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 & Selvakumar 2002). CIPP installation in small diameter service laterals (4–6 inches/100–150 mm) may be challenging (Wade & Johnson 2007). Furthermore, sharp bends, transitions, and massive roots are common conditions in laterals and are difficult for CIPP installation. Some structural defects in laterals, like hardened deposits and tuberculation, may obstruct the cleaning phase of lateral CIPP projects (Belanger & 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 & Hasan 2014).

Table 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) ii. Requirement of temporary bypass due to the flow in the pipes and groundwater level iii. Temporary access road construction in the case of sensitive areas iv. Access problems of larger diameter plugs originating from smaller manhole diameter v. Inspection and cleaning issue for force mains vi. Requirement of special arrangement for resin impregnation in large diameter tubes vii.Challenging site access and layout
B. Water main	i. Access problems in water main pipes ii. Requirement of digging, shoring of pits, and other open-cut activities iii. Incompatibility of the CIPP liners with the operation of the valves iv. Before the installation of CIPP, plugging water main service connections over 1.5 inches (40 mm) is difficult and may require digging
C. Lateral	i. Difficulty accessing the cleanout ii. Access issue for cleaning and liner installation due to absence of cleanout iii. Probability of CCTV equipment blockage iv. Substantial and recurring root intrusion problems v. Infiltration issue prior to liner installation

Pre-installation

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

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 a pre-liner, but this results in a substantial cost increase (Cuellar & Yong 2015). If the quantity of flow in the 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 such as densely populated and traffic congested areas make the bypass design more complicated and require additional costs (Ferguson *et al.* 2011; Westervelt & Rodenberger 2011). Referring to issue A. iii. in Table 1, for some sensitive areas such as wetlands and forests, transportation of liners and lining equipment is a significant concern and may require temporary access road construction before initiating CIPP installation (Ramirez *et al.* 2010). Another problem may arise prior to sewer main CIPP installation if the manhole diameter is smaller than the diameter of the plugs; therefore, suitable plugs should be invented to address this occurrence (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 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, wet out at the shop is not possible, and it requires special arrangements to impregnate or wet out the liner with resin onsite (Westervelt & 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, wet out tent, tractor trailer, etc.), and the resin tankers need access to come and go during wet out (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 the requirement for 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 2). This requires digging and shoring, removal of the asphalt and concrete structure, and cutting 6–8 feet of the exposed host pipe (Lueke *et al.* 2015; Rosenberg & Anderson 2015). While the rehabilitation work itself 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 connections to water mains (Leitch *et al.* 2015). As CIPP liners are not compatible with the operation of valves, valves 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 1, plugging and reinstatement of service connections over 1.5 inches (approximately 40 mm) 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 & Anderson 2015).

Figure 2 | Access pit with pipe removed (right) and bypass (left) (with permission from Matthews *et al.* 2015).

Access is the main problem for CIPP liner installation in laterals if the liner is installed through a cleanout. Most of the cleanouts, which are essential access points for lateral cleaning and installation, are located in backyards or basements, making them difficult to access (Wade & 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, 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 protruding lateral tap, the camera may become trapped in the lateral (Behe *et al.* 2012). If the lateral has significant and repetitive root intrusion problems, untreated roots can grow between the cured liner and host pipe. Eventually, a larger annular space may be created that will initiate underground infiltration and deformation of the liner. In this case, chemical root treatment should be exercised in advance of lining (Lee 2006).

Challenges during installation

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

Significant elevation changes have been known to cause problems during CIPP installation. For instance, the CIPP installation of combined sewer overflow pipes by the Northeast Ohio Regional Sewer District (NEORSD) faced 45 feet (13.72 m) elevation difference at one site and 60 feet (18.3 m) elevation difference at another. Consequentially, the contractor handled considerable issues, including hydrostatic pressure on the downstream terminus of the CIPP

Table 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 ii. Problems due to excess resin and improper impregnation iii. Issues originating from improper curing for thermally cured liners iv. Construction hassles from too much heat in the case of UV curing process v. Long installation time for large diameter pipes vi. Crystallization of roots in the services because of resin migration in curing phase
B. Water main	i. Inaccurate installation pressure ii. Issues with using excess amount of resin iii. Problems originating from failure to maintain a suitable combination between ambient temperatures at installation and pull rate
C. Lateral	i. Noise disturbance to the occupant ii. Presence of air in the tube during onsite resin impregnation iii. Problems with water curing due to higher inflation pressure with significant elevation changes iv. Challenges to monitor the curing temperature perfectly in both upstream and downstream sides of the pipes v. Problems created from pipe sagging and improper curing during liner installation

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 site visit in Edmonton, Alberta, the resin blew out from the liner due to the use of excess resin and improper impregnation. Improper curing (either under or overcuring) of the thermally cured liners is a significant problem in the CIPP process. Curing temperature and time are the two most important parameters that are intimately linked, and if the perfect combination between them is not properly followed during the curing process, the end product may suffer damage or wrinkles or folds may occur in the liner. In the case of the UV curing process, allowing the temperature to spike too high may melt the inner film, allowing it to adhere to the inside of the liner creating construction difficulties (Matthews 2013). To resolve this issue, the curing of the CIPP must take into account the existing pipe material, the recommendation from the resin manufacturer, and ground conditions (temperature, moisture level, and thermal conductivity of the soil).

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, a liner installation in the City of Los Angeles North Outfall Sewer (NOS), which is 78 inches (1,980 mm) in diameter and 1,800 feet (549 m) long, took approximately 7 days to complete (Hanks *et al.* 2010).

Handling of roots in the service lateral is another obstacle that may occur during the liner curing process, caused 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 & 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 & 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 & 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 wet out of the flexible tube is generally executed in the field, and errors can occur during the process. For example, due to uncontrolled wet out, air that is left in the tube will lead 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 simplest method with reduced equipment footprint. However, ambient cure time may range from 2 to 12 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 lead 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 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 & Rapp 2015).

Post-installation

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

Table 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 ii. Variation of liner thickness within the existing pipe iii. Liner peeling due to improper sealing after vacuum impregnation iv. Water re-entering the system after mainline rehabilitation 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 ii. Occurrence of longitudinal fold after liner installation iii. Wrinkles and voids occurring iv. Variations in the host pipe diameter v. Reinstatement problems of smaller sized water main service pipes
C. Lateral	i. Incidence of deficiencies such as liner lift, peeling, and wrinkles

The literature review shows a significant number of deficiency incidences following CIPP installation. Downey & Koo (2015) 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. 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. This problem may arise due to improper sealing after vacuum impregnation and poor workmanship. Addressing this liner peeling required a costly spot repair. Figure 3 depicts vacuum impregnation inside a wet out shop, peeling of liner after installation, and spot repair to resolve the liner deficiency.

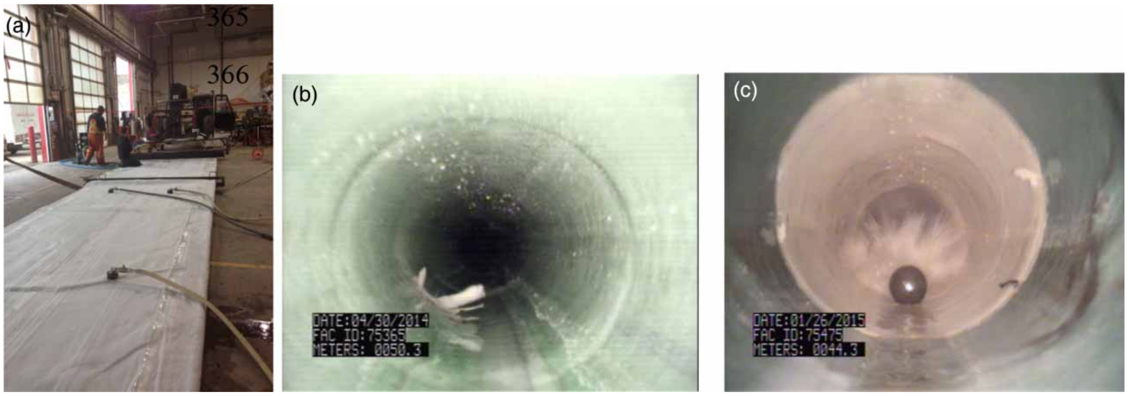

Figure 3 | (a) Vacuum impregnation and sealing, (b) liner peeling, and (c) spot repair.

Figure 4 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

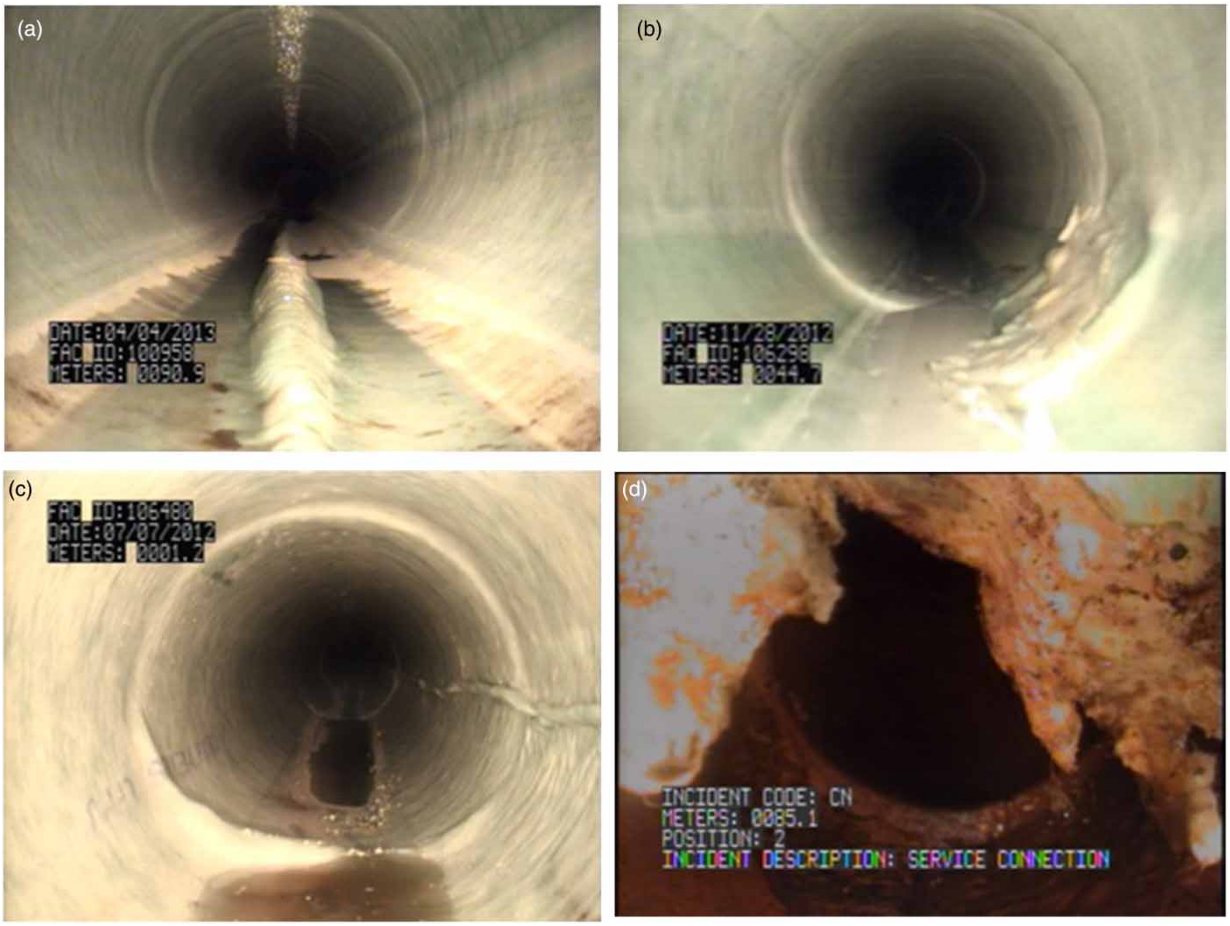

Figure 4 | Different liner deficiencies of sewer main CIPP: (a) fold in liner, (b) liner peeling, (c) wrinkles or bubbles, and (d) service undercut.

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 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 5, after successful CIPP installation, lined pipe sections have been connected by PVC pipe (Matthews *et al.* 2015).

A study by Davison & Coté (2015) shows the occurrence of a fairly large longitudinal fold after liner installation that obstructs the use of reinstatement and CCTV equipment. 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, such a fold resulted in high stress concentrations that develops along the longitudinal fold. However, potentially undesirable effects can be alleviated by controlling the oversizing of the virgin liner. This study proposed a QC criterion, which was called ‘allowable oversizing ratio (AOR)’; AOR is a function of the pipe’s internal diameter, gap dimensions, and surge pressure (Jaganathan *et al.* 2007). To reduce the risk of premature failure in heavily deteriorated pressure pipes, limiting the oversizing of CIPP liners is an effective quality control criterion (Jaganathan *et al.* 2007).

Figure 5 | Lined pipe sections connected by PVC pipe (with permission from Matthews *et al.* 2015).

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 extended over a portion of the internal service connections (Wong *et al.* 2015). This prevented the robotic cutter from identifying the location of those connections, and hence open-cut excavation and installation of such service connections was needed (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 typically occur if the external circumference of the liner exceeds the internal circumference of the host pipe. From split-disk tests 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 or 13 mm) from a smaller size water main (less than or equal to 6 inches/150 mm) is limited (Davison & Coté 2015).

Several post-installation deficiencies, such as 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 6 illustrates deficiencies in lateral liners (liner fold and peeling) found from CCTV inspection after CIPP installation in Edmonton city lateral rehabilitation projects.

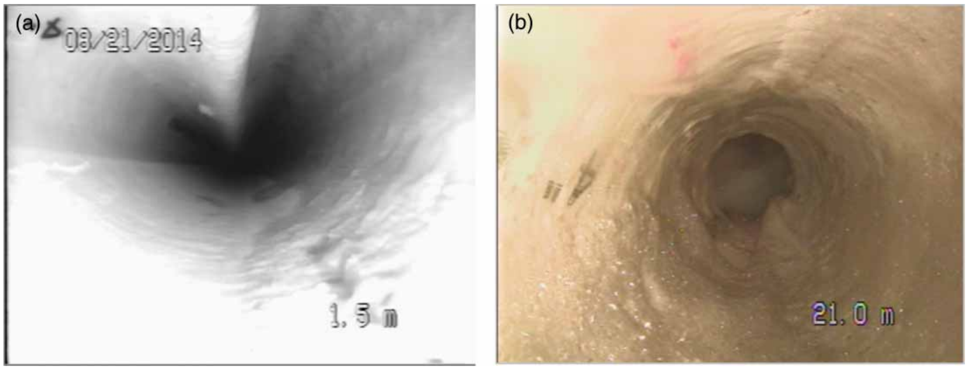

Figure 6 | Post-installation deficiencies in lateral: (a) fold in liner, (b) liner peeling.

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 according to Donaldson (2009). Environmental challenges on surface water or aquatic habitat are basically applicable for culvert and storm water drainage pipes that have water sources downstream. Table 4 shows the environmental issues regarding CIPP installation.

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 & Koo 2015). Of particular concern 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. The US Environmental Protection Agency (EPA) has classified styrene as a mutagen and considered it as potentially carcinogenic (Donaldson 2009). For aquatic species, styrene may be noxious if beyond certain concentrations (Baer *et al.* 2002). Although most of the CIPP installation projects for storm sewers are successful, the literature reveals that spills of uncured resin in just a small number of CIPP installations resulted in large fish kills.

Table 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 ii. Issues of styrene used in the resin complex, which is poisonous for aquatic habitats provided styrene concentration surpasses the standard contamination level iii. Fish deaths due to spills of uncured resin from CIPP installations iv. Presence of different carcinogenic chemicals v. Elevated COD, VOC, and metal levels due to CIPP condensate vi. Air quality issues due to styrene and VOC emission from CIPP application

For instance, about 3–4 gallons (11.4–15.14 L) 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 for drinking water at five of the seven study sites (Donaldson 2009). 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 (Donaldson 2009). 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 monitoring results denoted that organic materials remained in the environment for at least 35 days after CIPP installations.

According to the National Association of Sewer Service Companies (NASSCO), air emission of 0.5 ppm styrene is typical during CIPP activity, and styrene emitted by the CIPP process is far below the styrene exposure limits for healthy adults (20–25 ppm according to the International Toxicity Estimates for Risk). However, a few reports reveal that CIPP application may create environmental challenges by emitting styrene and other VOCs in the air. For instance, during a CIPP application in Birmingham, UK, nearby residents were complaining about noxious fumes inside their homes. Results from an indoor air test in one house showed styrene levels of 200 ppm, and CIPP contractors advised some residents to evacuate their homes (Bourbour Ajdari 2016). Whelton *et al.* (2012) compiled numerous indoor air contamination anecdotal reports from building residents near the CIPP sites, and the highest indoor air styrene concentration found was 500 ppm. A major finding of this study was that indoor air contamination incidents have occurred, but quantitative air monitoring data are lacking. However, VOC emissions into the air from CIPP operations are poorly documented and understood (Bourbour Ajdari 2016).

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).

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 review in this field, the following problems were identified and corresponding suggestions are tentatively made for future research:

- Aging and deteriorating infrastructure conditions are significant concerns for the cleaning step in the CIPP process; these conditions include cracks, internal corrosion, grease build-up, root intrusion, joint misalignment, separation, leakage, excessive pipe deflection, and lateral connection leakage. 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.
- No specific North American design standard exists for CIPP installations in sewers with non-circular sections. Currently, there are some European standards which are not followed in North American countries.
- 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 wet out, 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. There are now some sensors available to mitigate this issue.
- Different post-installation liner deficiencies such as 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, effective measures are needed to prevent styrene release; non-styrene-based resins are likely to become more widely used in the future.

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 and hence many potential advancements in the application of CIPP technology remain to be developed. This paper 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 review may benefit trenchless CIPP companies and water distribution and wastewater municipality sectors. Further study is suggested to quantify the frequencies of the major risks of CIPP in the future.

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