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Current water main rehabilitation practice using trenchless technology

Yichen Wu[a], Chao Kang[b], Mohammad Molavi Nojumi[a], Alireza Bayat[a,*]
and George Bontus[c]

[a] Department of Civil and Environmental Engineering, University of Alberta, 9211 116 street NW, Edmonton, AB, Canada T6G 1H9

[b] School of Engineering, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada V2N 4Z9

[c] Director of Engineering, Insituform Technologies Limited, 5743 68 Street, Edmonton, AB, Canada T6B 3P8

*Corresponding author. E-mail: abayat@ualberta.ca

Abstract

The market for water infrastructure rehabilitation is growing rapidly due to the increasing age of underground utilities. Currently, two common water main rehabilitation methods exist: cured-in-place pipe (CIPP) and polymer spray-on coatings. CIPP can provide structural support for both internal and external loads, while spray-on techniques provide chemical resistance as well as adding minor strength to the existing pipe. This paper summarizes water main rehabilitation practice using CIPP and spray-on methods. The history of trenchless rehabilitation technology is discussed, as well as current methodologies and products for water mains. The design, installation, and monitoring of water main rehabilitation products are also summarized, along with the associated risks. Quality assurance and control (QA/QC) methods are included for evaluating existing products and procedures.

Key words: CIPP, potable water pipes, QA/QC, rehabilitation, spray-on liners, water mains

Highlights

- Summary of the current state of practice of water main rehabilitation using trenchless technology, specifically CIPP and spray-on methods.
- Demonstrate the difficulties of water main rehabilitation comparing to sewer pipe rehabilitation.
- Illustration of the advantages of using CIPP technology for the rehabilitation of water mains comparing to other methods.

INTRODUCTION

Urbanization has increased rapidly since the 1980s. It is predicted that people living in urban areas will reach 66% of the total population by 2050 (United Nations 2015), which means approximately 2.5 billion additional people living in cities. Fast-growing urban populations will result in increased demand for efficient water and wastewater services. Underground water distribution systems have been aging and deteriorating since their original installation, with many reaching the end of their service life. According to the *Canadian Infrastructure Report Card*, as of 2018, most pipe infrastructure supplying potable water in North America will be over 50 years old (CI 2019) and its condition will continue to deteriorate. Eventually, issues such as pipe blockage, leaks, and poor water quality will emerge (Grigg 2005), along with the associated economic, environmental, and social impacts. However, emerging problems can be mitigated at an early stage, using well-established condition assessment programs and appropriate rehabilitation methods.

With the aging of potable, waste, and storm water systems, utilities have growing concerns regarding the possible health and safety risks to citizens, including poor water quality, and pipe leakage causing sinkholes. A survey by Canadian Municipal Asset Management assessed the current condition of Canada's water infrastructure and found that approximately 12% of water systems are in poor or very poor condition and require immediate maintenance (CI 2019). Some 20% are in fair condition (i.e. no immediate threats), but close monitoring and renewal are suggested to prevent potential failures. These studies have also indicated that early investments to restore pipe conditions can significantly reduce both the rate of pipe deterioration and long-term repair costs (CI 2019). It is estimated that, in Canada, about 60 billion CAD (approximately 47 billion USD) should be spent on immediate water infrastructure replacement or rehabilitation over 10 years for pipes in poor to very poor condition, according to the *Canadian Infrastructure Report Card* (CI 2019). For pipes in fair condition, the corresponding replacement/rehabilitation cost was estimated at 100 billion CAD (approximately 78 billion USD). These values suggest that a large amount of work is projected for water pipe rehabilitation. Selecting appropriate rehabilitation or replacement methods will, therefore, be essential in providing cost-effective construction, saving capital budgets and thus benefiting citizens (Zhao & Rajani 2002).

In general, pipe deterioration and breakage can be dealt with using proactive or reactive approaches (Grigg 2019). The reactive approach is used mainly by water utilities, such that when a pipe break occurs or a noticeable pipe failure is observed, a pipe rehabilitation or replacement method will be implemented. A proactive approach involves early analysis of the condition of the water system to anticipate and mitigate failure before it occurs (Grigg 2019). Grigg suggests that effective data base analysis supports early identification of issues and generally leads to improvements in overall water main condition. However, many utilities are currently attempting to improve their technologies in terms of condition assessment and monitoring, while data analytics are rarely implemented for water main assessment (Butler *et al.* 2017). In this context, it is necessary to investigate and implement methods for water main renewal. The most common method of replacing or renewing underground utilities has been open trench construction. However, this is difficult, especially in populated areas, since coming across structures and facilities at the surface is inevitable. Most often, open trenching increases capital costs and inconveniences the public, and, in some cases, it is difficult or impossible to carry out (Wassam 2015). However, trenchless technologies have definite advantages for the rehabilitation of underground infrastructure. These include safer working conditions, as well as lower project costs and less environmental impact than open-cut methods, while being more efficient and productive than conventional methods (Hashemi *et al.* 2011). Safer working conditions are achieved, since equipment is usually used underground for trenchless methods, rather than people. Also, since construction is more efficient and productive, the process involves less crew hours and downtime, resulting in a smaller carbon footprint and lower project costs (Beale *et al.* 2013). In general, open trenching is more practical and cost efficient for projects in shallow conditions (Apeldoorn 2010). However, for projects that are deeper or located in densely populated areas, cost reductions ranging from 20 to 60% can be achieved with trenchless technology compared to conventional open cut methods (Mohammad *et al.* 2008).

After four decades of improvement and innovation, trenchless construction methods are applied to underground projects worldwide. They have been evolving in different application areas and for different purposes. Examples of trenchless technologies for new infrastructure include pilot tube micro-tunnelling (PTMT), which is used to install new underground pipes; tunnel boring machines used for tunneling; and pipe bursting for replacing old pipes (along the same path). On the other hand, trenchless rehabilitation methods include cured-in-place-pipe (CIPP), slip lining, and spray-on linings, which are all used for pipe rehabilitation. These diverse technologies have helped improve the efficiency of the underground construction industry, and provide benefits in terms of public health and safety (Bontus 2012).

If the construction area is restrained, such as when underground utilities are crowded or in congested residential areas, both pipe bursting and slip lining will be more disruptive than CIPP or spray-on linings, due to the larger access area required (Hashemi *et al.* 2011). In these cases, CIPP and spray-on methods would be better solutions since the equipment requires less space at ground level (Lanzo Lining Services 2010). Open excavations are required at service connections for both pipe bursting and slip lining, which results in a significant increase in work and cost (Hashemi *et al.* 2011). In contrast, using CIPP, service connections can be reinstated internally after installation using robotics and closed-circuit television (CCTV) equipment. After decades of advancement, CIPP has become the most popular method for rehabilitation of water pipes due to its quick installation and the limited space required for access (Sterling *et al.* 2009). Nonetheless, research on design standards for water main rehabilitation has fallen behind the development of rehabilitation technologies. Design standards for CIPP for water mains must account for high pressures in operational pipes and pressure surges, as well as monitoring requirements for rehabilitated water mains.

Aside from CIPP, which covers a range of semi structural to fully structural pipe rehabilitation, spray-on lining is another trenchless rehabilitation option. Cracks and defects in water pipes not only result in water leakage, but can also allow contaminants (e.g. heavy metals) from the surrounding soil and/or corroded host pipe to leach into drinking water (Ellison *et al.* 2010). Spray-on cement mortar or epoxy provides a coating on the internal surface of the pipe, which prevents further corrosion, biofilm accumulation and tuberculation of the host pipe, thus maintaining a safe potable water delivery system (Ellison *et al.* 2010). It is most applicable, however, if an assessment of the host pipe determines that it is structurally sustainable over a long period, since spray-on lining is currently designated as a non-structural solution. Epoxy has some strength on its own, so that if a thick layer is applied, it can support the existing structure for a short period; however, this solution is costly compared to CIPP rehabilitation. Furthermore, with application of a thick layer of epoxy, long-term deformation cannot be ruled out and safety aspects – in terms of its ability to withstand pressure – cannot be guaranteed (Ellison *et al.* 2010). Until now, polymer spray-on lining has been widely applied for water distribution systems of 15 to 30 cm (6 to 12 inches) diameter and has proven beneficial in many cases. One advantage of spray-on lining is fast application times (even compared to CIPP): in most cases, construction takes only one day and thus a service bypass can be avoided (Ellison *et al.* 2010). The effort required for service reinstatement for spray-on methods is also much less than for CIPP, since applying negative pressure or blowing air through the service pipes can easily remove the thin polymer film that covers the service connections after application of the liner (Ellison *et al.* 2010).

It is important to have an understanding of the condition of different pipe materials present within water transmission/distribution systems and assess such systems before pipes begin to deteriorate (CI 2019). Water main rehabilitation has not been prioritized until recent years, when it was recognized that water utilities lose up to an estimated 40% of drinking water from current distribution systems (Mutikanga *et al.* 2011). All things being equal – that is, the same pipe size, magnitude of failure, soil conditions, and break location – the cost impact due to a water main break will be higher than for a damaged sewer. In addition, damage to drinking water systems creates other issues that eventually cost more to fix. For instance, the problem is particularly evident when the ground above gives way, which can destroy nearby infrastructure (e.g. roadways and other structures). Broken water mains are also a threat to public health and safety, and increase the risk of water contamination.

Compared to rehabilitation of sewers, water main rehabilitation using CIPP is more challenging and complex. For instance, sewers can be accessed for CIPP using available manholes; however, CIPP rehabilitation of water mains requires excavation of access pits. The water main needs to be shut off, and a service bypass implemented to ensure uninterrupted water supply (Allouche *et al.* 2014). Also, water main pipes are generally smaller in diameter than sewers, so personnel generally rely on CCTV to perform inspections. In cases where there is severe tuberculation inside a water pipe, it may not be feasible to access the entire length of the service line, even with small inspection equipment. Furthermore, water mains are pressurized systems and the CIPP product needs to be designed to withstand relatively high internal pressures, as well as pressure surges. More importantly, product development for CIPP used in water mains is limited, as lining products used in potable water pipes must not cause health effects. CIPP installations in water mains must also meet local regulatory requirements. In North America, one standard that must be met is NSF/ANSI 61 (Estelle 2016), which covers materials used in water distribution systems with respect to their effect on water quality. A comparison of requirements for pressurized versus gravity main rehabilitation is given in Table 1.

Table 1 | Comparison of CIPP rehabilitation requirements for gravity main and pressurized main systems

	Gravity Main		Water Main		
Challenges	**Required?**	**Resolved?**	**Required?**	**Resolved?**	**Comments**
Cleaning	✓	Yes	✓	Yes	
Service bypass and pumping	✓	Yes	✓	Yes	Expensive
Access pits	No	N/A	✓	Yes	Unavoidable for water mains
Service connection reinstatement	No	N/A	✓	Yes	May require external service reconnection
Disinfection	No	N/A	✓	Yes	
NFS/ANSI 61 requirement (North America)	No	N/A	✓	Yes	
Approved design standards	✓	Yes	✓	No	Partial for water mains
Low pressure consideration	✓	Yes	✓	Yes	Current water main pressure design uses same design method as for gravity mains
High pressure consideration	No	N/A	✓	No	
Surge pressure consideration	No	N/A	✓	No	

With increasing numbers of projects involving rehabilitation of potable water pipes worldwide, rehabilitation companies have been improving product design to compete in the market. At least four companies currently provide products for rehabilitation of potable water mains – Table 2. The existing products, however, were designed according to American Society for Testing Materials (ASTM) standards for pipes with low or no pressure (ASTM F1216-16 2016), and do not take into account high pressure surges and temperature effects. Nevertheless, proprietary CIPP liner products have been evaluated by research and development teams before use in rehabilitation projects in the field, and many such projects have been completed successfully.

WATER MAIN REHABILITATION ADVANCEMENTS

CIPP products and installation methods have improved significantly over the years. These developments have increased the options available for maintenance of aging sewer and water systems, and greatly reduced costs for government and industry.

Development of water main rehabilitation methods

Before CIPP was introduced, deterioration of pipe interiors was inhibited by cement mortar spray-on linings (AWWA 2014). This method was first used for water systems in New Jersey, USA, in 1933

Table 2 | CIPP liner products

Company	Product	Diameter range	Installation length	Internal pressure capability	Installation method	Certification	Composite material	Internal surface	Structural class
HammerHead and RS Technik (Pipe Aquatec 2015)	BlueLine	150 to 1,200 mm (6 to 48 in)	N/A	Up to 1,586 kPa/230 psi (<305 mm/12 in) up to 1,000 kPa/145 psi (>305 mm/12 in)	Inverse and Pull-in	NSF/ANSI 61	Resin-saturated polyester and fiberglass	N/A	Class IV
Insituform/Aegion	Insitumain®	100 to 2,400 mm (4 to 96 in)	400 m (1,312 ft)	1,034 + kPa (150 + psi)	Inverse	NSF/ANSI 61	Resin-saturated polyester (PE100) and fiberglass	Polypropylene coating	Class IV
Sanexen Water Inc. (Sanexen Water Inc. n.d.)	Aqua Pipe	150 to 600 mm (6 to 24 in)	300 m (984 ft)	1,034 + kPa (150 + psi)	Pull-in	NSF/ANSI 61	Woven polyester and polymeric membrane	Polyurethane membrane	Class IV
Sekisui (Sekisui SPR Americas, LLC 2018)	Nordipipe™	150 to 1,200 mm (6 to 48 in)	300 m (984 ft)	1,379 + kPa (200 + psi)	Inverse	NSF/ANSI 61	Resin-saturated polyester and fiberglass	Polyethylene coating	Class IV

Note: Companies are listed in alphabetical order. Mention of specific company names is in no way intended to be an endorsement of a particular product (Aegion/Insituform 2017).

(Ellison *et al.* 2010). It was only used on large-sized pipes, since the sprayer had to be dragged manually by workers. Remote sprayers were invented in the 1950s, enabling rehabilitation of smaller pipes using this method (Ellison *et al.* 2010). Cement mortar deteriorates quite easily, however, raising the pH over time and affecting water quality, so polymer products were developed for use in water mains. Epoxy came onto the market early in the 1980s and came into use across Europe and Japan (Ellison *et al.* 2010). Spray-on epoxy was accepted by US markets late in the 1980s, and standards were developed for its use. The spray-on method was finally approved by the American Water Works Association (AWWA) for use in the USA in 2008 (Ellison *et al.* 2010). Recent developments in polymer lining for water mains involve the use of epoxy, polyurethane and polyurea, which have faster curing times than epoxy (Dudley 2000).

CIPP-based pipeline rehabilitation began in the UK in 1971 (Lee & Ferry 2007). The idea of rehabilitating pipes without open trenching began when Wood (the founder of UK-based Insituform Technologies (Kozman 2013)) was working on a leaking pipe in a location that was difficult to access, making it difficult to replace. After successful implementation, the new CIPP process was commercialized and patented in 1977. In 1994, the United States patent for CIPP expired, allowing the process to be used by other companies. CIPP was not widely adopted in North America until the early 2000s (Kozman 2013); however, its use was reported in Winnipeg, Canada, and the USA in the 1970s (G. Bontus, personal communication, 2018). The design flexibility, ease of installation, wide range of applications, and ability to accommodate different pipe shapes (as well as sizes and direction changes), make CIPP an almost ideal method for gravity pipe rehabilitation (Kozman 2013). Initially, it was implemented on projects involving pipes ranging from 50 to 3,000 mm in diameter (2 to 120 inches) (Kozman 2013). The progressive development of spray-on methods and CIPP for pipe rehabilitation is summarized in Figure 1.

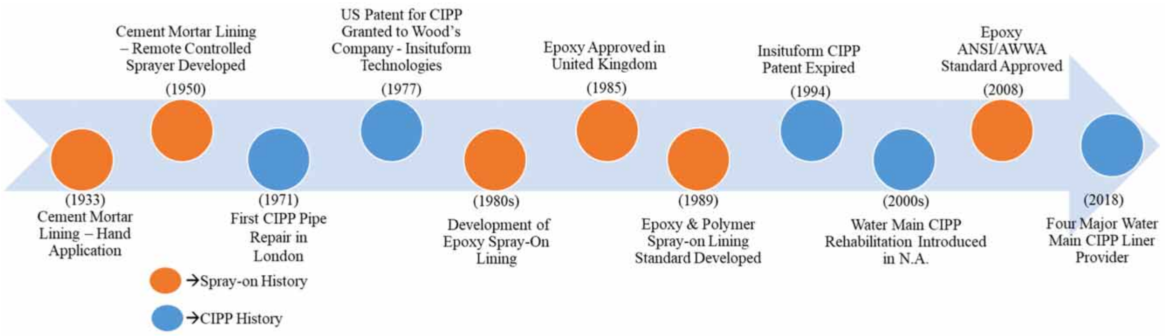

Figure 1 | Timeline of key advances in spray-on methods and CIPP for pipe rehabilitation.

Water main markets and products

Currently, most CIPP water main rehabilitation projects worldwide are designed and implemented using liner products from one of the companies listed in Table 2. The companies typically provide lining services in regions close to their corporate offices; in other regions, local contractors may be licensed to perform installations using their products/technologies.

Figure 2 shows the marketing locations of the four corporations, and it is noted that the most developed regions have the most competitive markets. This is because countries such as the UK, USA, Canada, Australia, and Japan, etc., where water pipes were constructed in the late 1800s and early 1900s, have aging pipes that now need rehabilitation or replacement. Therefore, more rehabilitation projects are undertaken in these regions.

The companies offer different liner product designs, including the composite material, installation method, and internal pressure capability (see Table 2). For small diameters, liners can be

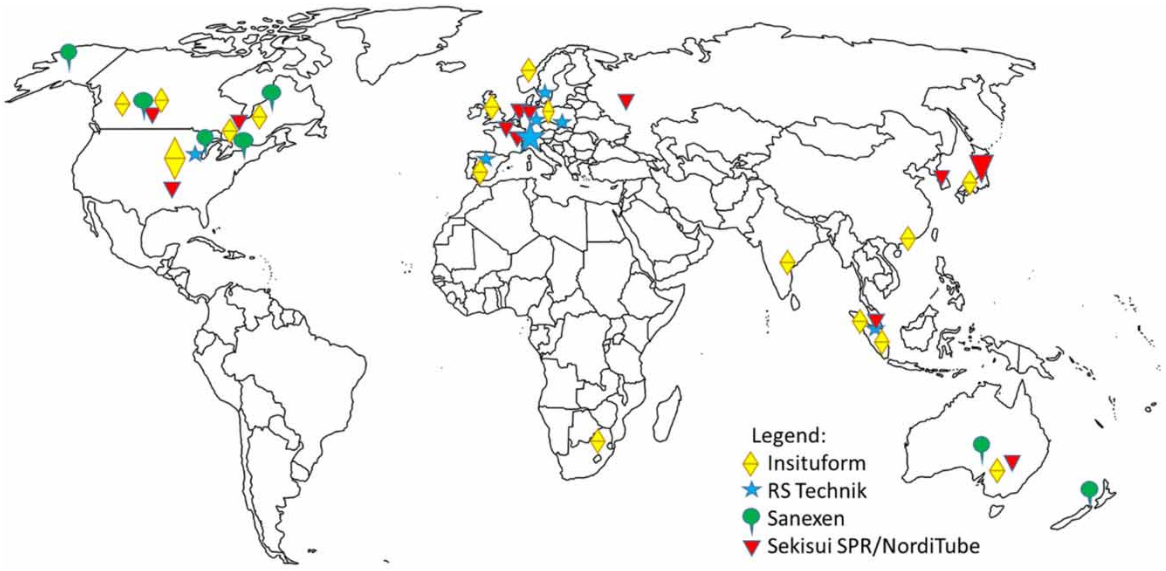

Figure 2 | Current CIPP Water Main rehabilitation marketing.

manufactured and installed in pipe exceeding 15 cm (6 inches); however, Insituform can line pipes as small as 10 cm (4 inches). Insituform has lined sewers as large as 240 cm (96 inches) in diameter, while the Sanexen product has been used in pipes of up to 60 cm (24 inches). In terms of internal pressure, all four companies provide products that can withstand pressures exceeding 1,034 kPa (150 psi). Polyester, vinyl ester and fiberglass are commonly used for water main rehabilitation by CIPP. However, polymer epoxy resin is the most widely used material: not only does it provides better bonding and tensile strength between the CIPP liner and host pipe, but it is also easier to certify to the NSF/ANSI 61 standard for potable water distribution systems.

STRUCTURAL CLASSIFICATION OF CIPP LINERS

Before selecting the appropriate water main rehabilitation method and product, the structural condition and degree of deterioration of the host pipe must be determined. For gravity pipes, the liner design depends on the deterioration status. In ASTM F1216, design considerations for CIPP liners are presented for both partially and fully deteriorated pipes (ASTM 2016). In fully deteriorated pipes, failure is imminent with cracks and holes present. Partial deterioration describes pipe conditions when joints leak, there is root infiltration and/or exfiltration occurs.

For repair or rehabilitation of water mains and pressurized pipes, product selection also depends on the structural condition. Liner products are divided into four classes according to AWWA M28 *Rehabilitation of Water Mains* – Class I for non-structural repairs, class II and III for semi-structural repairs, and Class IV for full structural repairs (AWWA 2014). Non-structural repair (Class I) is for cases when the host pipe is structurally sound, but requires internal joint seals and cathodic protection. The ideal method in this case is spray-on lining. Semi-structural repair (class II and III) involves interactive liners like CIPP; however, the liner is not required to withstand burst failure of the host pipe or long-term pressure application. Class II and III liners differ in that Class II liners rely on adhesion to the host pipe, while Class III liners rely on inherent ring stiffness. It should be noted that minimum inherent ring stiffness (class III and IV) relates to the self-supporting ability of the liner when the pipe is depressurized. Full structural repair requires independent liners (Class IV). Class IV is applicable to cases when the host pipe has entirely failed and the CIPP liner must have the capacity to support both internal and external loads. The M28 operations manual incorporates a table with suggestions on the structural classification of liners but does not provide quantitative design guidelines or standards (AWWA 2014). Currently, industrial design of pressure liners and coatings relies on ASTM F1216, but the criteria are often misinterpreted or used improperly (Bontus, personal communication, 2017).

LINER DESIGN AND INSTALLATION CRITERIA

Since the introduction of rehabilitation methods for underground pipes, developments in engineering design methodology are directed towards extending the service life of water mains more efficiently, while ensuring that baseline requirements are met. The related ASTM standards provide guidelines for the design and installation of liner products. Local water associations are also involved in determining that the liner product and design are applicable to pressurized potable water transmission/ distribution pipes.

In North America, the AWWA M28 operations manual is always considered (AWWA 2014), along with the appropriate ASTM standards for water main rehabilitation projects. The M28 manual does not provide a quantitative design process, but does illustrate the essential steps involved in a water main rehabilitation project.

Both AWWA and ASTM contribute to ensuring that design and construction standards are satisfactory for public water systems (see Table 3). While AWWA standards only apply to potable water systems, those from ASTM provide detailed design, installation, and quality assurance procedures for different types of water systems, and different rehabilitation methods. The standards for pipe rehabilitation design and installation standards are presented in Table 3. They were established for CIPP rehabilitation of sewers (using inversion or pull-in installation methods), as well as spray-on liners for potable water pipes (ASTM 2016). However, no standard has yet been developed for design and installation for water main rehabilitation using CIPP. Currently, the design of products for CIPP rehabilitation of water mains relies entirely on equations in ASTM F1216 (ASTM 2016), which specifies design requirements for determining the minimum CIPP liner thickness for low pressure pipes. However, the conditions present in water mains, including water pressure surge cycle and maximum water pressure present in these systems, are not sufficiently taken into account in F1216. Futhermore, without consideration of these pressure characteristics, the liner may not be able to support the maximum pressure in a water surge or the higher sustained pressure in the systems compared to low pressurized system. The lack of

Table 3 | Summary of resources for gravity and water main rehabilitation (North America)

Method	Standard	Title	Date	Design application
CIPP	ASTM F1216	Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube	2016	Gravity mains
	ASTM F1743	Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe	2017	Gravity mains
Spray-On	ASTM F3182	Application of Spray-Applied Polymeric Liners Inside Pipelines for Potable Water	2016	Water mains
CIPP/Spray-on	AWWA M28 (manual)	M28 Rehabilitation of Water Mains	2014	Water mains
Point repair CIPP	ASTM F2599 2016	The Sectional Repair of Damaged Pipe by Means of an Inverted Cured-in-Place Liner	2016	Gravity mains
UV-cured CIPP	ASTM F2019 2011	Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)	2011	Gravity mains

design standards taking into account the high-pressure conditions within water systems could result in pipe breakage, and the damage resulting from such an incident could be disastrous.

INSTALLATION PROCEDURES

Installation procedures for CIPP and spray-on rehabilitation require much less time and labour compared to conventional dig and replace methods. Water main rehabilitation using either CIPP or spray-on methods usually involves installation of a temporary service bypass, excavation of access pits, cleaning of the internal pipe surface, and the lining process, as well as pre- and post-lining inspections. In addition, surface restoration work needs to be done to complete the project.

Service bypass

As installation may take a few days, the pipe requiring rehabilitation must be shut off during the process. A service bypass (meeting NSF/ANSI 61) must be set up before installation starts to provide local water supply. Service bypasses often involve the use of butt-welded high-density polyethylene (HDPE) pipes connected to nearby fire hydrants (Matthews *et al.* 2012a, 2012b). The HDPE pipe system is treated using a disinfectant to ensure the quality of the water supply (Reilley *et al.* 2015).

Access pit excavation

Once the host pipe is shut down and the service bypass is set up, access pit excavation can begin. Access pits are often excavated at the points where pipes change directions, with the dimensions of the pits depending on the geometry. Once access pits are excavated, a section of the existing pipe is cut out for access during subsequent installation activities.

Cleaning

The internal surface of the host pipe must be cleaned for effective installation of a CIPP liner. Table 4 shows the cleaning methods, along with their advantages and disadvantages. The most common methods used previously involve hydraulic jetting, mechanical drag cleaning, chain flails, and swabbing. More recent cleaning technologies involve pulling a variety of grades/types of abrasives or

Table 4 | Methods for cleaning service pipes before rehabilitation

Method	Advantages	Disadvantages
Flushing	Removes impurities	Does not remove tuberculation
Air scouring	Removes film and lightweight debris	Does not remove tuberculation Service connection must be isolated
Drag cleaning with chain scraper	Removes internal encrustation and hard deposits	Potential damage to service connections
High pressure flushing		
Foam pigs and swabs	Removes internal encrustation and hard deposits	Pig receiver station required
Power boring	Removes internal tuberculation and corrosion	May damage service connections
Abrasives with low-pressure vacuum	Does not involve water Exposes hidden cracks at service connections Minimizes damage to pipe wall and service connections	High cost

stones through the host pipe using a low-pressure vacuum system to remove tuberculation and debris (Cooper & Knight 2013).

Pre-lining inspection and service plugging

Once the internal surface has been cleaned, a pre-lining inspection is conducted to record the condition of the internal surface of the pipe and any visible defects that could affect the lining installation and performance. A pre-lining inspection is essential for detecting leaks and any remaining tuberculation, as well as identifying issues that may affect the lining process.

For CIPP, service connections are also plugged at this stage. Capping service connections prevents resin from flowing into and blocking the smaller pipe. The plugs are made of polyester materials (i.e. PE or HDPE) and installed with an air-actuated piston and cartridge device on the robot (Matthews *et al.* 2012a, 2012b). For reinstatement of service connection locations after CIPP, all service connection locations are recorded during the pre-installation inspection using remote-controlled CCTV, making reinstatement easier after lining. Typically, plugs for CIPP are made of materials such as PE and HDPE, and they are installed using remote robotic devices (Matthews *et al.* 2012a, 2012b).

In contrast to CIPP, rehabilitation using spray-on lining does not require capping, since the liner sprayed at the service connections can easily be removed using pressure afterwards.

Lining

Lining is the key step of the rehabilitation process. All other activities are done to ensure that this step is successful. Both spray-on lining and CIPP involve similar preparation, but in most cases the spray-on lining process is easier to implement as it does not involve inserting a pre-formed liner and service connections do not need plugging.

Spray-on liner

Before applying the spray-on liner, the material must be prepared according to specifications (e.g. temperature, mixing requirements). The robotic spraying equipment is introduced at the access point and traverses the cleaned pipe. The rotational speed and rate of movement of the device depend on the pipe diameter, and are determined by the operator. Several application layers may be required to build up the desired resin thickness. The minimum thickness of the applied layer is 1 mm (0.04 inches) (ASTM F3182 2016).

The materials used for polymeric spray-on linings are polyurea, polyurethane or epoxy (AWWA C620 2019). These polymers provide a durable coating on the internal surface of the pipe, which increases both flow rate and water quality and enhances the pipe condition (Rajasärkkä *et al.* 2016). A minimum temperature of 3 °C is usually required to cure the resin (ASTM F3182 2016). While the spray-on method is applicable for almost all types of host pipe material, there are limitations. Consistent lining thickness is not guaranteed throughout the entire pipe length and adhesion cannot be not ensured without testing (Bontus, personal communication, 2018).

CIPP lining

The installation process for CIPP is much more complex than for spray-on linings. Two installation methods exist, inversion and pull in, with both methods used worldwide. For the pull-in method, the polyurethane coating is inside the liner during set up, while, for the inversion method, the coating is on the outside of the liner. The two installation methods require significantly different processes and equipment, but each can be equally beneficial for a project, subject to project requirements and site conditions (Lanzo

Lining Services 2010). For instance, when one major section of the pipe requires repair or limited access is available, the pull-in method will be better. The inversion method, however, provides better control during liner expansion and is better for pipes with larger diameters (Lanzo Lining Services 2010).

In the inversion method, moderate water or air pressure is used to physically expand the folded liner into the host pipe circumference (ASTM F1216 2016). For the pull-in method, the same expansion options apply (according to the ASTM standard). However, based on field experience, pigs should be used to expand the liner during pull-in (Bontus, personal communication, 2018). To install the liner using inversion, it is inserted into the downpipe inside out, so that when the liner is inverted, the impermeable surface becomes the internal surface (ASTM F1216 2016). A hydrostatic head is introduced with enough water pressure to invert the liner.

In the pull-in technique, a calibration hose is used to expand the pulled-in pipe to size. A second access pit is excavated for pull-through. The resin-saturated liner is pulled into the desired location with the outer coating outside. The calibration hose is then inverted into the pulled-in liner, in a process similar to inverting a CIPP liner. The inverted calibration hose may be removable, such that once the pulled-in liner is inflated and cured, the calibration hose is not in contact with the resin and can be removed when installation is complete. On the other hand, a non-removable calibration hose becomes part of the liner – the resin is absorbed, and the calibration tube cures and bonds tightly against the fabric tube (ASTM F1743 2017).

To cure the resin, devices are attached to each end of the liner and host pipe to circulate hot water or steam through the rehabilitated section. To ensure effective curing of the liner and resin, ASTM F1216 specifies that hot water needs to be retained in the pressurized pipe at 80 °C for 90 minutes. Steam curing, which is less common, requires a shorter time interval. After curing, the liner is cooled to below 38 °C (ASTM F1216 2016). The temperature and time required for curing depend on the product used and liner thickness, as well as other onsite variables.

The liner may be saturated with resin where it was manufactured or onsite immediately before installation. Temperature-controlled reefer trucks are used to transport the resin-saturated liner. Often, a CCTV camera and robot are used to monitor and control the installation remotely. Inversion installation typically requires scaffolding to set up a water column for pipes between 30 and 40 cm (12 to 16 inches) in diameter to provide the head required to invert the liner inside the host pipe. Composite liners are used in CIPP, with the woven polyester or fiberglass/felt layers allowing penetration of resin through the liner, and the glass fibre providing additional strength. The epoxy or vinyl ester resin used also provides resistance to corrosive chemicals and adds strength to the liner after it hardens, which supports the internal and external loads.

Post-lining hydrostatic pressure testing and service reinstatement

After the lining process is complete, a hydrostatic pressure test is needed before service reinstatement, to ensure that the makeup water (water lost due to evaporation and/or leakage) does not exceed local municipal requirements. Subsequently, service connection reinstatement and post-lining CCTV inspection can be carried out. Usually, service connections can be reinstated internally using a remote-controlled robot (the same one used for plugging, but this time equipped with an air drill bit), based on the locations determined during the pre-lining inspection. Sometimes there are issues such as folds at service connection locations, or plugging failure causing resin to block the connections. In these cases, external reinstatement is required (Matthews *et al.* 2012a, 2012b).

Site restoration

The rehabilitated pipe portion must be reconnected once all installations and inspections are complete. Any hydrants and valves involved in the installation also have to be replaced. The restored section of the host pipe is reconnected using new flanges. Rehabilitation of smaller diameter pipes may not require flanges; instead, a coupling is used to reconnect the rehabilitated section. To ensure safe connections, end seals should also be installed.

Site restoration after CIPP or spray-on lining includes backfilling of access pits, as well as reinstating any surface disruption (e.g. grass, pavement). Much less restoration is required for rehabilitation conducted using CIPP or spray-on lining than for open-cut methods.

QUALITY ASSURANCE AND CONTROL

Quality assurance and control (QA/QC) are distinct processes which, when integrated, ensure that project design meets safety requirements and complies with relevant standards and procedures (including the materials used). QA relates to the overall process, which in CIPP covers multiple steps (wet-out, installation, curing, post-installation inspections, sample collection and testing, etc.). QC is used to verify whether a product design is acceptable, and involves activities like mechanical tests and measurements.

The ongoing development of products and processes has resulted in successful water main rehabilitation projects being completed worldwide. Although these technologies present minimal safety risks, issues and challenges with water main rehabilitation still exist. The bonding between the pipe and liner cannot be checked after installation unless a pipe section is taken out of service for testing, for instance. Also, no standard has been developed for pressurized water main rehabilitation. Such issues restrict the growth of CIPP technology.

In addition to laboratory tests to check the structural performance of liners, short- and long-term monitoring methods are available for water main rehabilitation projects. Often, however, such monitoring is not done because it is inefficient or increases project costs significantly. The hydrostatic pressure test is always performed after rehabilitation to confirm that the mechanical performance of the liner meets requirements. The other most common physical test after rehabilitation – measurement of liner thickness – can be conducted from the access pit.

Site investigation and water sample tests

An assessment of the surrounding ground conditions is important before rehabilitation. While ensuring that construction can be performed safely, it also facilitates a better understanding of the current pipe condition. Soil sample tests provide information on soil properties, including the rate and extent of corrosive behaviour (Matthews *et al.* 2012a, 2012b). Water sample collection and testing is regulated to ensure that the potable water supply is safe after installation (Reilley *et al.* 2015).

Post lining in-situ tests

The in-situ tests required in North America when lining is complete are listed in Table 5. Hydrostatic pressure tests ensure that the lined pipe provides service without leaking. Hydraulic testing ensures that the condition/quality of the internal surface pipe is satisfactory and the rehabilitated pipe is clear of obstructions; it is rarely done, however. Thickness measurements help to assess the quality of the liner product and installation by enabling comparison of the design and actual thicknesses.

Laboratory testing

Table 6 lists tests that can be performed on the liner product and the composite. These tests are QA/QC measures to ensure that the water main liner meets or exceeds basic design standards. Strength-related tests include flexural, tensile, compression, buckling, negative pressure, and pressure design tests; these are used to evaluate the liner performance after installation (Awe 2017). The values

Table 5 | Post-lining field tests (North America)

Test	Description	Associated Standards/ References
Hydrostatic pressure	Pipe pressurized with water to twice operating pressure or operating pressure 345 kPa (+50 psi) and monitored continuously for at least one hour	ASTM F1216 2016 ASTM F1743 2017 (Alzraiee *et al.* 2013)
Hydraulic	Hazen-Williams C-factor used to determine pressure loss caused by friction	Matthews *et al.* (2014); Allouche *et al.* (2011); Alzraiee *et al.* (2013)
Liner thickness	Caliper or ultrasonic measurement	ASTM F1216 2016 ASTM F1743 2017 (Alzraiee *et al.* 2013)

Table 6 | Liner performance laboratory tests

	Method	Description	Standards and References
Strength-related	Flexural test	Flexural strength determined using three-point loading system until sample yields or breaks; peak bending stress and flexural modulus should be higher than design value	ASTM D790 2017 (Knight & Sarrami 2006; Herzog *et al.* 2007; Riahi 2015)
	Tensile test	Tensile strength of liner determined by stretching sample until it yields or breaks; tensile peak stress should be higher than design value	ASTM D638 2014 (Knight & Sarrami 2006; Herzog *et al.* 2007; Riahi 2015)
	Compression test	Liner or liner/host pipe deflection characteristics determined under parallel plate loading	ASTM D2412 2011 (Herzog *et al.* 2007; Riahi 2015)
	Short-term burst test	Liner deformation or failure characteristic determined by applying pressure all round, simulating in-situ conditions	ASTM D1599 2014
	Negative pressure testing	Liner deflection determined using negative pressure in internal pipe	Matthews et al. 2012a, 2012b; Allouche *et al.* (2011)
	Hydrostatic design basis	Evaluation of strength regression of liner and host pipe	ASTM D2992 2012
Complimentary	Peel test	Peel or stripping characteristics of adhesive bond for epoxy	ASTM D903 2017
	Immersion test	Submersion of steel pipeline in deionized water, weak acid, weak base	AWWA C210 2008 (Awe 2017)
	Puncture test	Shear strength of liner before resin saturation	ASTM D732 2017
	Liner ovality test	Ovality after compression (should be within 5% of allowable maximum)	Matthews et al. 2012a, 2012b; Allouche *et al.* (2011)
	Hardness testing	Penetration into the liner material by specified tool	ASTM D2240 2015
	Raman spectroscopy	Degree of aging of liner material	Matthews *et al.* 2012a, 2012b; Allouche *et al.* (2011)

determined should be equal to or above the manufacturer design values. Peel, puncture, liner ovality, hardness, and Raman spectroscopy tests are complementary tests used to assess whether the product meets or exceeds the required performance.

RISKS AND CHALLENGES

Determining the condition of a buried pipe accurately before rehabilitation is challenging but essential. The principal method currently used to understand the condition of old pipes is monitoring the quality of water outflow and the amount of water lost. Most analyses of water loss are desktop studies based on knowledge and experience, rather than through field inspections.

Critically deteriorated pipes may not be possible to rehabilitate using CIPP lining. Instead, replacement of deteriorated pipe with new pipe may be required. Even if partially deteriorated pipe can be repaired using CIPP, the degree of deterioration and any major defects should be noted for the installation crew. A geotechnical report is required for the area, and the surrounding site conditions and nearby utilities should also be determined at the design stage (Selvakumar *et al.* 2012).

Every step of CIPP installation in water mains involves risks. Many of these risks are unavoidable, due to the nature of water main rehabilitation, and apply to all rehabilitation methods (e.g. service bypass, ensuring water quality, access pit excavation, and surface reinstatement). However, some issues specific to CIPP – including liner products, resin, and installation and curing methods – can be gradually improved (Rogers & Louis 2008).

After the pull-in and curing process, any excess resin – that is, resin not bonding the liner and pipe – poses a potential risk. Other issues include folds in the liner fabric (which cause difficulty during service reinstatement and affect the pressure capability of the rehabilitated pipe), cap/connection misalignment, and resin penetration through the plug causing blocking (Jaganathan *et al.* 2007). Water mains have hundreds of service connections providing water to households and buildings. Although the development of remote-control CCTV and robotic technology for internal reinstatement have helped to improve efficiency, issues still arise and external reinstatement of service connections may be necessary. According to Selvakumar *et al.* (2015), around 5% of service taps in water main projects had to be reinstated externally. However, in practice, about 50% to 90% must be reinstated externally. Consequently, minimizing the need for external reinstatement during installation can lower costs and reduce project duration.

The lack of long-term performance verification for CIPP is another potential risk: after years of wear and deformation, the liner is often not retested to check its condition. In addition, no standard exists for baseline qualification testing after liner installation (Matthews *et al.* 2012a, 2012b). QA/QC procedures must be enhanced for water main rehabilitation with CIPP, and the entire service life of the liner needs to be assessed based on field data (Selvakumar *et al.* 2012).

MONITORING

Short and long-term monitoring methods are available for checking the structural performance in CIPP water main rehabilitation projects. These methods are not implemented often, however, as they are inefficient.

One monitoring method is ultrasonic examination using smart pigging technology (Varela *et al.* 2014). The internal surface of the pipe can be mapped before and after lining, and gaps between the liner and host pipe can be detected using ultrasonic waves. The disadvantages of smart pigging are cost and practicality – in 2018, testing a 100 m section of pipe could exceed 100,000 CAD (approximately 78,600 USD). Nonetheless, smart pigging could be an excellent in-situ test method if the cost issue is resolved.

CONCLUDING REMARKS

Water main rehabilitation has increasingly become important around the world. Methods like CIPP and spray-on polymer linings are largely accepted as alternatives to traditional open trenching. Four major CIPP manufacturers and service providers – Insituform (UK), RS Technik (Switzerland), Sanexen (Canada), and Sekisui (Japan) – have products approved under NSF/ANSI 61 for use in potable water pipe rehabilitation.

In North America, requirements for water main rehabilitation using CIPP are still based on ASTM standards for sewers (i.e., low pressure systems) to determine the minimum liner thickness. A major limitation is that water pressure surges in pressurized mains and maximum pressure limitations are not taken into account under these standards.

For water main rehabilitation using CIPP, a service bypass is always required. A service bypass may not be required with spray-on lining methods, as such installations are considerably faster than CIPP. New robotic technologies can be used to reinstate service connections in lined pipes after CIPP installation. This reduces the total time for installation and lowers costs.

Conducting field and laboratory tests related to liner performance is good practice before a project. These tests should be conducted as part of QA/QC for all ongoing projects, but, due to cost, they are not implemented regularly. Procedures for evaluation of baseline and long-term liner performance should also be established, along with innovative monitoring methods.

Water main rehabilitation using trenchless methods such as CIPP and spray-on lining has greatly helped in renewing aging potable water pipes.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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