

Innovative research program on the renewal of aging water infrastructure systems

Ariamalar Selvakumar, John C. Matthews, Wendy Condit and Ray Sterling

ABSTRACT

The needs associated with the aging water infrastructure are immense and have been estimated at more than \$1 trillion over the next 20 years for water and wastewater utilities. To meet this growing need, utilities require the use of innovative technologies and procedures for managing their systems. To help meet their needs, the U.S. Environmental Protection Agency initiated a research program to assist utilities in the renewal of water distribution and wastewater collection systems and this paper summarizes that program. This paper addresses the state-of-the-art review of current and emerging renewal technologies available for water distribution and wastewater collection systems. This paper also discusses the results of other program components which are intended to aid in the use of the renewal methods. This included: a cured-in-place pipe retrospective study of liners in use for more than 25 years; a field demonstration program of innovative water rehabilitation methods; a review of quality assurance and quality control measures for trenchless technologies; and current decision-making models and methodologies available to support rehabilitation versus replacement decisions.

Key words | decision support, pipe rehabilitation, quality assurance/quality control, trenchless technology, wastewater pipe, water pipe

Ariamalar Selvakumar (corresponding author)
Urban Watershed Management Branch,
Water Supply and Water Resources Division,
National Risk Management Research Laboratory,
Office of Research and Development,
U.S. Environmental Protection Agency,
2890 Woodbridge Avenue (MS-104),
Edison, NJ 08837,
USA
E-mail: selvakumar.ariamalar@epa.gov

John C. Matthews
Battelle, 7231 Palmetto Drive,
Baton Rouge, LA 70808,
USA

Wendy Condit
Battelle, 505 King Ave.,
Columbus, OH 43201,
USA

Ray Sterling
Louisiana Tech University,
P.O. Box 10348,
Ruston, LA 71272,
USA

INTRODUCTION

In the USA, there are approximately 16,000 wastewater systems incorporating approximately 740,000 miles (1,190,660 km) of public sewers plus 500,000 miles (804,500 km) of private lateral sewers. Some components of the US wastewater infrastructure are well over 100 years old. The combination of age, neglect, and mishaps gives rise to approximately 50,000 sanitary sewer overflows (SSOs) per year, along with the resulting illnesses and environmental degradation and as much as 10 billion gallons of raw sewage released yearly (EPA 2004). The latest 2013 infrastructure report card issued by the American Society of Civil Engineers provides a 'D' grade for wastewater infrastructure (ASCE 2013). ASCE estimates that nearly \$300 billion is needed for capital investments over the next 20 years (ASCE 2013).

The drinking water infrastructure in North America is older than the wastewater infrastructure. In the USA, there are approximately 166,000 drinking water systems, comprising over 1 million miles (1.6 million km) of pipes (Grigg 2004). Of these systems, there are more than 50,000 community water systems serving approximately 95% of the population (EPA 2013a). An estimated 34% of the water mains are more than 25 years old, 73% are ten-inch diameter or smaller, and 90% are made of asbestos cement, cast iron (CI), ductile iron (DI), and PVC (AWWA 2004). ASCE gave water infrastructure a 'D' grade in its 2013 report card and indicated that leaking pipes lose an estimated seven billion gallons of clean drinking water a day (ASCE 2013). AWWA estimates that nearly \$1 trillion is needed for restoring and expanding

the drinking water infrastructure over the next 25 years (AWWA 2013).

As part of the U.S. Environmental Protection Agency's Sustainable Water Infrastructure Initiative, research is being conducted to improve and evaluate innovative technologies that can reduce costs and increase the effectiveness of the operation, maintenance, and renewal of aging drinking water distribution and wastewater conveyance systems (EPA 2007). This initiative is aimed at encouraging the introduction of new and improved technologies into the US marketplace for water and wastewater rehabilitation, which will help utilities provide reliable service to their customers and meet their statutory requirements. The outputs from this research program are intended to assist U.S. EPA program and regional offices to implement Clean Water Act (CWA) and Safe Drinking Water Act requirements; to help states and tribes meet their programmatic requirements; and to assist utilities to more effectively implement comprehensive management of drinking water distribution and wastewater conveyance systems.

This program has identified the many key challenges and issues associated with water infrastructure system rehabilitation (Selvakumar & Tafuri 2012). A series of reports have also been produced on the state of technology for rehabilitation of gravity wastewater systems (mains, laterals, and manholes), sewer force mains, and water mains (EPA 2009, 2010a, b, 2013b). In addition, a review of quality assurance and quality control (QA/QC) measures for trenchless rehabilitation technologies was conducted to obtain feedback from technology vendors and utilities on best practices and lessons learned (EPA 2011a). Also, current decision-making models and methodologies available to support rehabilitation versus replacement decisions were analyzed (EPA 2011b). As part of this research effort, a critical gap was identified in determining the long-term performance of rehabilitation technologies, which prompted a retrospective evaluation of cured-in-place pipe (CIPP) in sewer rehabilitation (EPA 2012a). Two field demonstrations of innovative and emerging technologies were conducted in 2010 to demonstrate the applicability of water main rehabilitation (EPA 2012b, c). The program is still continuing with the development of databases for retrospective evaluation and renewal case studies and more field demonstrations of innovative rehabilitation technologies. The key findings of the program are summarized herein.

GRAVITY SEWER REHABILITATION

The drivers for almost all sewer rehabilitation works in the USA are the regulatory requirements associated with SSOs and combined sewer overflows (CSOs), including both gravity sewers and force mains. The tools available to the sewer utility engineers have changed remarkably over the last 60 years (EPA 2010b). Trenchless technologies for gravity sewer renewal (i.e., repair, rehabilitation, and replacement) have made significant penetration into the US market with estimates of the proportion of work carried out using trenchless techniques ranging up to 70% in the sewer sector (Carpenter 2013). There is still considerable room for improvement in existing trenchless technologies and/or in the development of new technologies (Tafari & Selvakumar 2002). In addition, the average rate of system renewal and upgrades in the USA cannot keep pace with increasing needs, quality demands, and continually deteriorating systems.

Renewal technologies

The most commonly used technique for renewal of gravity sewer mains is CIPP, but there are a range of technologies available to address specific conditions and site constraints in the existing sewer system for rehabilitation or replacement. Repair techniques include internal and external repair sleeves, short sections of CIPP liners, and robotic repairs using in-pipe robots. Rehabilitation techniques include sliplining, a variety of CIPP approaches, close-fit lining technologies, and grouting approaches to seal leaky pipes that are otherwise structurally sound. Replacement techniques include pipe bursting and related techniques that will install a new pipe on the same alignment as the existing pipe and conventional and trenchless methods for replacement of the existing pipe on a new alignment. Table 1 summarizes the available technologies for gravity sewer rehabilitation.

Technology gaps and future research needs

Gaps between available technologies in the marketplace and technological developments that would offer significant

Table 1 | Summary of gravity sewer rehabilitation technologies

Technology	Description	Dia.	Max. length (ft)	Deterioration level	Lateral connections	Cleaning required ¹
Cementitious lining	Cementitious lining applied to a cleaned and dried host pipe wall	4" to 160"	2,000	Partial	Reinstated when blocked	High
Polymeric lining	Spray-on lining applied to a cleaned and dried host pipe wall	4" to 108"	2,000	Partial	Not normally blocked	High
Sliplining	Insertion of a new pipe and grouted for structural support	6" to 160"	1,500	Partial or fully	Must be excavated	Low
CIPP	Insertion of impregnated liner and cured with water, UV, or steam	4" to 108"	2,000	Partial or fully	Reinstated robotically	High
Close-fit lining	Insertion of a deformed liner reverted back to a original shape	4" to 60"	1,500	Partial or fully	Must be excavated	Medium
Pipe bursting	Insertion of new pipe while bursting or splitting the host pipe	4" to 48"	1,000	Fully	Must be excavated	Low
Spiral wound lining	Insertion of a thermoplastic profile that is grouted for structural support	6" to 120"	450	Partial or fully	Reinstated robotically	Medium

¹High: thorough cleaning and preparation required; Medium: moderately cleaning required; Low: very little cleaning required.

improvements in practice were identified as part of this research effort. Technology gaps vary with the specific sectors of the wastewater collection system, but significant needs remain in matching the design procedures to the actual loading conditions that the rehabilitated pipe will experience in the field and in controlling the field processes to provide high QA/QC of the finished product across a wide range of projects and contractors. Technology advances, if achieved, would promote cost-effectiveness, increase performance of the rehabilitated product, and provide higher levels of QA for the owner.

Most rehabilitation systems appear to be performing effectively to date, but a better understanding of expected life-cycle and deterioration rates is important to properly utilize asset management systems. Some key gaps exist in the availability of non-destructive inspection and condition assessment tools including: thickness and material property measurements for pipe walls and liners; identification of annular gaps and voids; data sharing among municipalities to allow the improved prediction of deterioration rates and life-cycle costs (LCC); and the ability to tie the specifics of improved longevity created by rehabilitation to asset management indicators.

Nearly 100 different rehabilitation technologies were identified as part of this research effort and 78 detailed technology profiles were developed for innovative and

emerging rehabilitation technologies for gravity sewers (EPA 2010b). Some of these technologies have been used internationally for nearly 40 years and in the USA for around 30 years; while other technologies have been recently developed or newly introduced into the USA after substantial experience overseas (EPA 2010b). The U.S. EPA demonstration program provides the opportunity to demonstrate models for the acceptance of new products, the creation of QA/QC protocols, and the creation of protocols that will capture the as-installed condition of rehabilitation technologies, thus providing the basis for the tracking of their LCC and performance. In combination with the demonstration of practical protocols for the retrospective evaluation of previously installed rehabilitation technologies, this program is helping to create a better understanding of the role of trenchless rehabilitation in the management and operation of wastewater collection systems.

FORCE MAIN REHABILITATION

Force mains that carry sewage flows under pressure represent a special set of challenges for sewer rehabilitation. Force mains represent about 7.5% of the wastewater systems and typically use materials that are not commonly used in

gravity sewer systems such as DI, CI, steel, and concrete pressure pipe (Selvakumar *et al.* 2011). In contrast to the nation's gravity sewer and water supply systems, the use of force mains to convey sewage is relatively recent. Approximately 68% of the force mains in use today have been in service for 25 years or less, while another 30% have been in service between 25 and 50 years and only 2% beyond 50 years (Thomson *et al.* 2007). Therefore, although the current market is not large, the need for rehabilitation technologies for force mains is expected to grow over time in order to prevent an increase in failures as the associated infrastructure ages.

Historically, the most common renewal technology employed has been to replace the force main using open cut construction. Part of the reason for that choice has been a lack of rehabilitation technologies appropriate for sewer force mains. There is a wealth of technologies available for gravity sewers, but the field has been limited for pressurized systems. Fortunately, this situation is changing as more technology vendors recognize the growing opportunity in sewer force main rehabilitation.

As some of the newer rehabilitation technologies develop a positive track record of use in sewer force mains and the confidence in their design approach and installation process strengthens, more utilities will be willing to consider these trenchless technologies as potential renewal solutions. Trenchless methods have proven themselves to be cost-effective for gravity sewer mains, especially when both direct and indirect costs associated with a replacement program are considered. A similar outcome is expected for sewer force mains once data on the effectiveness and longevity of these technologies and materials and LCCs become more readily available.

Renewal technologies

Renewal of force mains includes repair, rehabilitation, and replacement. The estimate of renewal works in force mains is between 250,000 and 600,000 linear ft or 0.08 to 0.19% of the total length on an annual basis (Selvakumar *et al.* 2011). Force mains can operate with a wide range in pressures (from a few ft of head to hundreds), so there are potentially a large number of technologies that can be adapted to force mains from other applications.

Some of the technologies presented in the state-of-technology report (EPA 2010a) have not been used in a sewer force main to date, even though they have properties that make them suitable for this application. Vendors are constantly making improvements to their products, so it is wise to consult them before using any of the identified technologies. Over 60 conventional, innovative, and emerging rehabilitation technologies for force mains are discussed in the report. Detailed technology profiles are included as an appendix for over 30 innovative and emerging technologies for force main rehabilitation (EPA 2010a). A few observations are provided below on renewal technologies for force mains. Table 2 summarizes the available technologies for sewer force main rehabilitation.

Technology gaps and future research needs

It is clear that a system renewal program for force mains needs to integrate several aspects and to have a broader vision than merely the rehabilitation technology and its implementation. The elements that need to be integrated within the scope of an asset management approach include inspection, condition assessment, maintenance, renewal, and funding. Some observations on technology gaps and future research needs in these areas are listed below

- *Rehabilitation technology considerations for force mains.* Despite being developed either for water mains or gravity sewers, several trenchless technologies can readily be adapted for use in force mains. CIPP has a limited track record of use in force mains. The emergence of new CIPP systems based on woven fiberglass and UV-curing, which provides a stronger liner with enhanced hoop strength, also has applications in force mains. One method of assisting owners in their efforts to apply some of these emerging technologies is to publish the findings of demonstration projects and case studies. Also, promoting the increased use of decision support systems (DSS) is important in order to help utilities ask the right questions so that a viable rehabilitation solution emerges.
- *Design considerations for force mains.* One of the key data elements needed is verification of the long-term

Table 2 | Summary of sewer force main rehabilitation technologies

Technology	Description	Dia.	Max. pressure ¹ (psi)	Max. length (ft)	Service connections	Cleaning required ²
Polymeric lining	Spray-on lining applied to a cleaned and dried host pipe wall	4" to 60"	150	650	Not normally blocked	High
Sliplining	Insertion of a new pipe and grouted for structural support	4" to 110"	150	1,000	Must be excavated	Medium
CIPP	Insertion of impregnated liner and cured with water or steam	4" to 120"	150	1,000	Reinstated robotically	High
Close-fit lining	Insertion of a deformed liner reverted back to original shape	4" to 60"	150	3,000	Must be excavated	Medium
Pipe bursting	Insertion of new pipe while bursting or splitting the host pipe	4" to 48"	150	1,000	Must be excavated	Low
Expandable PVC	Insertion of a pipe heated and pressurized to the host pipe shape	6" to 30"	150	500	Must be excavated	Medium
Melt-in-place	Liner heated by an air-driven pig and pressurized tightly to the host	6" to 12"	150	500	Reinstated robotically	High

¹The maximum pressure will vary for different materials and products within a technology category.

²High: thorough cleaning and preparation required; Medium: moderately cleaning required; Low: very little cleaning required.

performance of pressurized rehabilitation systems. For example, a gap exists in terms of a design procedure for CIPP in pressurized applications to ensure that long-term performance requirements can be met. Currently, ASTM F1216 is used in the USA, but it was primarily designed for gravity applications. In addition, the combination of tensile strain and potential chemical attack from wastewater can create strain corrosion problems in polymeric resin-based materials. The potential for strain corrosion in CIPP materials in pressurized wastewater applications needs to be understood and taken into account in the design procedures developed. Currently, only gravity CIPP liners are tested for strain corrosion per [ASTM D5813 \(2008b\)](#).

- *Maintenance considerations for force mains.* Another capability gap is the access needed to the force main and the need to shutdown, dewater, and clean the main for rehabilitation. This is an inevitable feature of any internal rehabilitation technology, as it is for inspection technologies. There is a need for emergency repair procedures for lining systems and for utilities to be trained in their application. Lack of such procedures makes utilities reluctant to rehabilitate force mains, preferring replacement with materials for which they have emergency repair procedures in place.

WATER MAIN REHABILITATION

The water infrastructure in the USA is older than the wastewater infrastructure. At the current pace of replacement (less than 1% per year) and including new installations, the average age of the underground pipe infrastructure will gradually approach the commonly accepted design life of 50 years ([Matthews *et al.* 2013](#)). Many pipes have been known to operate longer than their design life, but the frequency of failures increases with the age of the infrastructure ([Heywood & Starr 2007](#)). This means that unless a more aggressive renewal program is adopted now for water distribution systems, communities are going to be hit with significantly increased repair costs in the not too distant future. The US water industry has a very different operational environment compared to the wastewater industry (which is subject to enforcement actions under the CWA). For this reason, the amount of renewal undertaken or even contemplated by water utilities is significantly less than wastewater utilities and therefore the state-of-technology for rehabilitation is not as advanced ([EPA 2013a](#)). Water distribution systems are also harder to inspect internally (under pressurized conditions) and require expensive and/or time-consuming temporary services and disinfection in conjunction with inspection and/or rehabilitation activities.

Renewal technologies

Renewal of pipes falls into one of three distinct categories (e.g., repair, rehabilitation, and replacement) (EPA 2013b). Repair techniques are used when the existing pipe can be readily restored to a structurally sound condition, providing the pipe has acceptable flow capacity and supports good water quality. Rehabilitation methods include internal coatings, sealants, and linings which are often used to extend operational life and restore much or all of the pipe's hydraulic capacity and improve water quality. Other rehabilitation methods are directed at restoring structural functionality. Replacement of an existing pipe is used when the main is severely deteriorated, collapsed, or increased flow capacity is needed.

Rehabilitation focuses on the renewal aspects of water mains where the existing pipe becomes part of the renewal work. If the rehabilitation is to provide only corrosion protection, or the existing pipe is only partially deteriorated, then the remaining structural strength of the existing pipe can be incorporated into the fabric of the completed

system. For fully deteriorated situations, the existing pipe acts merely as a right-of-way for the installation of the structural liner. The choice of method will largely depend on the perceived condition of the pipe, project objective, and estimated cost. Rehabilitation technologies include spray-on linings such as cement mortar, epoxy, polyurea, and polyurethane; segmental and continuous sliplining; CIPP linings; inserted hose linings; and close-fit lining by symmetrical reduction or fold and form. Pipe bursting can also be considered a rehabilitation or replacement method. Table 3 summarizes the available technologies for water main rehabilitation.

A significant component in water distribution system rehabilitation projects concerns service reinstatement and restoration or replacement of service lines. If a water line runs along one side of a street, then the service lines to the properties on either side of the street could be renewed quite differently. Frequently, 'short side' service lines involve open cut works in sidewalks, yards, and gardens, whereas 'long side' replacements may require lengthy excavations in road pavements and restoration of costly traffic-bearing

Table 3 | Summary of water main rehabilitation technologies

Technology	Description	Dia.	Max. pressure ¹	Max. length (ft)	Class	Service connections	Cleaning required ²
CML	Cementitious lining applied to a cleaned and dried host pipe wall	4" and up	N/A	1,500	Class I	Reinstated when blocked	High
Epoxy lining	Spray-on lining applied to a cleaned and dried host pipe wall	4" to 36"	150 psi	650	Class I	Not normally blocked	High
Polymeric lining	Spray-on lining applied to a cleaned and dried host pipe wall	4" to 60"	150 psi	650	Class II/III	Not normally blocked	High
Sliplining	Insertion of a new pipe and grouted for structural support	4" to 110"	150 psi	1,000	Class IV	Must be excavated	Medium
CIPP	Insertion of impregnated liner and cured with water or steam	4" to 60"	150 psi	1,000	Class IV	Reinstated robotically	High
Close-fit lining	Insertion of a deformed liner reverted back to original shape	4" to 60"	150 psi	3,000	Class II-IV	Must be excavated	Medium
Pipe bursting	Insertion of new pipe while bursting or splitting the host pipe	4" to 48"	150 psi	1,000	Class IV	Must be excavated	Low
Expandable PVC	Insertion of a pipe heated and pressurized to the host pipe shape	4" to 16"	150 psi	500	Class IV	Must be excavated	Medium
Melt-in-place	Liner heated by an air-driven pig and pressurized tightly to the host	6" to 12"	150 psi	500	Class IV	Reinstated robotically	High

¹The maximum pressure will vary for different materials and products within a technology category.

²High: thorough cleaning and preparation required; Medium: moderately cleaning required; Low: very little cleaning required.

surfaces. Renovation of service lines with longer runs may be an opportunity for a trenchless replacement option such as impact moling or ramming or a trenchless rehabilitation method such as lining. Traffic impacts and shallow burial may increase the likelihood of leakage and increase the need for pipe renewal. The technologies available for service line rehabilitation include epoxy lining and plastic liners, although their use is not common.

Technology gaps and future research needs

The available technologies for water distribution system renewal offer several benefits to open cut replacement, but they do leave some gaps in terms of certain needs that are unmet. These gaps fall into two main categories: data gaps in terms of knowledge of the existing pipe condition; and capability gaps in terms of the available renewal and rehabilitation technologies.

Accurate data on pipe condition are necessary for the successful selection and design of renewal technologies. Data gaps relate to the amount and/or quality of direct physical inspection data on a pipe, which may be obtained either externally or internally. Obtaining external data requires excavation for inspection on the pipe surface, which can be costly and impracticable, although vacuum excavation may be used to obtain data in a spot location. As a result, the sample size is extremely small and the confidence level of the findings in terms of being representative of the pipeline as a whole is very low. Internal data can be obtained over the full internal surface area of the pipe, but this typically requires the main to be shut down and dewatered for inspection, which is also costly due to the service interruption, although some technologies do exist for live inspections.

The available rehabilitation technologies in the market currently generally meet the required water distribution system renewal needs, but some capability gaps remain. Reopening service connections after lining still requires excavation with some technologies at each connection location for manual reopening and reconnection to the service pipe, often requiring a new fitting. Where service connections are frequent, this becomes as disruptive as a full-length excavation, thereby negating the benefits of some trenchless solutions. Operational aspects such as access requirements and the length of time that the main is out of service are

also areas where gaps exist between capability and customers' needs. A gap also remains in the understanding of the long-term performance of various rehabilitation technologies and their materials. These materials and methods have been introduced recently and therefore their installed performance has not been studied over time.

To overcome the barriers and gaps identified, it was recommended that innovative rehabilitation technologies be demonstrated in field conditions and measured against a clearly defined set of performance criteria, which can inform water utilities of the capabilities, applicability, and costs of innovative technologies. Two different technologies have been demonstrated to date (EPA 2012b, c), which are discussed later in this paper.

QA/QC BEST PRACTICES

Most rehabilitation methods are the result of proprietary ideas, which have developed into proprietary systems. As such, the standards for their design and use have been developed on a technique-by-technique basis. Many technical innovations evolve in this way with the design, construction, and other aspects of QA/QC being provided exclusively by the company offering the technology. The downside to this approach is the lack of understanding and control over the design details by the owners and their consultants. However, over time, most proprietary technologies will make a transition from this situation into one where most aspects of the design of the process are handled by the design engineer working on behalf of the owner. Best installation and QA/QC practices were reviewed for trenchless rehabilitation of sewer mains and water transmission mains as summarized in Table 4.

Case studies on how utilities handle QA/QC activities in the field during installation were collected from 12 utilities located nationwide that encompassed a range of small to large utilities and relatively new to experienced users of trenchless rehabilitation technologies. In the utility interviews, particular emphasis was placed on field oversight of projects and the types of 'as-built' information collected during the installation of the trenchless rehabilitation technology (EPA 2011a). It was also determined how the 'as-built' information was used by the utilities in their decision-making efforts to estimate the effectiveness of the technology, its future

Table 4 | Summary of best QA/QC practices

Technology	QA/QC practices
CIPP	<ul style="list-style-type: none"> • Submittal of documents detailing the material pre-qualification testing accomplished • <i>In situ</i> sampling either by restrained tube or flat plate to verify the finished CIPP's structural properties (Note: this was not recommended by the UV-light cure systems due to a cited conflict of the installation equipment with the area in which the sampling would have to take place) • <i>In situ</i> thickness by restrained tube or ultrasonic testing of the liner in the host pipeline • Post-installation CCTV inspection to confirm the liner's close fit and interior finish
Close-fit liner	<ul style="list-style-type: none"> • Submittals showing the materials to be used and their cell class testing as given in ASTM F1504 or F1871 • <i>In situ</i> sampling by a restrained tube to verify the liner's flexural properties and finished thickness per their materials and installation standards • Post-installation CCTV inspection to confirm the tightness of the fit with the host pipe and finish of the liner
Spray-on lining	<ul style="list-style-type: none"> • Surfaces to be treated must be cleaned of all oil, grease, rust, scale, deposits, and other debris or contaminants. The surfaces must be clean and (ideally) dry for the materials to be applied and bonded to the wall surface. Sprayed-on coatings or linings must be placed on competent surfaces • Thickness of the coating or lining system can be obtained by using a dry film thickness gage during the application of epoxy resins and other slower drying materials. The installed thickness of both epoxy and the quick curing polymeric systems can be obtained post-hardening by the use of a calibrated ultrasonic thickness gage • Defects in polymeric type coatings such as pinholes should be verified by spark testing and corrected • Adhesion of the polymeric coatings to the existing wall surface when a part of the performance of the coating should be confirmed by testing
Grout-in-place (GIP)	<ul style="list-style-type: none"> • Submittal of package showing the materials to be used and their pre-qualification testing carried out by the developers of the technology • Evaluate the effectiveness of the <i>in situ</i> grouting of the annular space by taking compressive strength samples of the grout used and by 'sounding' the finished liner for voids in the grouted section. Voids of greater than 5% would require spot grouting • Post-installation visual inspection using CCTV to document fit and finish of the liner
Pipe bursting	<ul style="list-style-type: none"> • Require submittals from the contractor demonstrating that the personnel doing the work have been properly trained in use of the equipment for the project. Included in these submittals will also be a detailed work plan demonstrating that the contractor has proper knowledge of the construction sequence and possible issues that must be dealt with, such as surface heaving or settlement, resulting from the proposed improvements • A post-installation CCTV inspection shall be done to confirm the as-installed condition of the new pipeline

maintenance requirements, and its probable life expectancy as part of their ongoing asset management activities.

The rehabilitation of pipelines generally does not carry the same sense of importance for construction observation and as-built documentation when compared to new construction (Selvakumar et al. 2012). In addition, it does not afford the same opportunity for construction observation because access is often limited by nature for trenchless rehabilitation technologies to the ends of the pipe or a few access pits. This may discourage utilities from undertaking rehabilitation technologies even if they may cost less. Better recognition is needed among utilities and vendors that trenchless rehabilitation technologies are part of a comprehensive rebuilding program for pipelines and structures. As utilities become aware of the benefits of more extensive data collection in

the field and consistent documentation of as-built data, their focus on developing and maintaining successful QA/QC programs will increase (WaterWorld 2011).

DECISION-MAKING TOOLS

A study of the current decision-making models and methodologies available to support rehabilitation versus replacement decisions was identified as a need early on in this research. The purpose of this task was to conduct: (1) an extensive literature review of the current models proposed throughout the world and (2) a national survey of water and wastewater utility practices, which included visiting eight large utilities and surveying an additional nine from across the United States (EPA 2011b).

Based on the model review and approaches used by the utilities visited and surveyed, four models were identified as offering the best practices for making rehabilitation versus replacement technology selection decisions. These models and approaches, which are summarized in Table 5, included:

- A geographic information system (GIS)-based model for selecting sewer main technologies based on applicability to project conditions, relative costs, and perceived benefits (Halfawy *et al.* 2008). This prototype can perform a multiobjective optimization of the renewal plan using a genetic algorithm to maximize condition, minimize risk, and minimize LCC.
- A fuzzy-based LCC model for selecting water main technologies based on cost-effectiveness (Ammar *et al.* 2012). The site-specific inputs of the model include breakage data and deterioration curves, installation and maintenance costs, and service life.
- A general model which incorporated a large technology database for water and sewer technologies (Matthews 2010). The evaluation was based on several site-specific parameters including host pipe characteristics (i.e., diameter, length, pressure, etc.) and site accessibility.
- The city of Atlanta's web-based Rehab Selection Tool (RST) used for their sewer rehabilitation program (Matthews *et al.* 2012c). RST allows the designer to get detailed views of the pipe defects and other parameters such as site photos, pipe characteristics, etc. The designers are able to make decisions as to the most cost-effective and least disruptive technologies.

Improving on the best practices is feasible if the best aspects of each of the models are incorporated into a

single model. The GIS-based model by Halfawy *et al.* (2008) contains an approach for including defect codes in the wastewater selection process and the LCC model by Ammar *et al.* (2012) incorporates main break and deterioration data into the selection process. The model by Matthews (2010) contains a robust database and thoroughly industry vetted evaluation process. The Atlanta RST has a platform for incorporating cost data for specific technologies, which could be expanded for more technologies based on utility cost data. Each of these four tools is capable of many of the critical analyses a DSS must have, but the primary gap in each is the lack of case study information, which would need to be added.

RETROSPECTIVE EVALUATION

During the early stage of the research project, the need emerged for a quantitative, retrospective evaluation of the performance of pipe rehabilitation systems. This need was reinforced at an international technology forum held in September 2008, where participants indicated that evaluation of past installations would prove to be a valuable addition to the planned field demonstration projects for innovative rehabilitation technologies. The rationale for the retrospective evaluation research is as follows:

- The biggest data gap in asset management involving rehabilitation is prediction of remaining asset life and how long rehabilitation techniques can extend that life. Municipalities have expressed a strong desire for some hard data on the current condition of previously installed systems to validate or correct the assumptions made at the time of rehabilitation.
- Since several of the major pipe lining techniques have now been in use for at least 15 years (some nearly 40 years internationally), it is a good time to undertake such an investigation to see if, on the basis of the current condition of the liner, the originally planned lifetime (typically 50 years) is reasonable (EPA 2010b).

The outcome of this evaluation will help to address one of the largest unknowns in terms of decision-making for engineers and LCC/benefit evaluations and to provide shared experiences among municipalities in a systematic

Table 5 | Best practices in existing decision-making approaches

Model/Utility tool	Water/Wastewater	Defect data	Number of methods	Case studies
Halfawy <i>et al.</i> (2008)	Wastewater	Yes	20	No
Ammar <i>et al.</i> (2012)	Water	Yes	9	No
Matthews (2010)	Water/ Wastewater	No	100	No
Atlanta (RST)	Wastewater	Yes	6	No

and transferable manner. The initial project focused on CIPP liners because they were the first trenchless liners (other than conventional slipliners) to be used in pipe rehabilitation and they hold the largest market share.

The pilot testing used CIPP samples from both large and small diameter sewers in two cities that were in excellent condition after being in use for 25, 23, 21, and 5 years, respectively (EPA 2012a). Testing on the liners included thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy. In addition, environmental data were gathered as appropriate including external soil conditions and pH, and internal waste stream pH. Three of the liners had already been in service for nearly half of their originally expected service life, but overall, there is no reason to anticipate that the liners evaluated will not last for their intended lifetime of 50 years and perhaps beyond (Allouche *et al.* 2014).

Additional work has been funded which focuses on CIPP and other rehabilitation methods including sliplining, fold-and-form liners, and deformed/reformed liners. The final outcome of that work will include a web-based database of retrospective samples that can be used to determine the actual life-cycle of various rehabilitation methods under various real-world conditions.

FIELD DEMONSTRATIONS

To date, two innovative technologies for water main rehabilitation have been demonstrated: one was a spray-on lining technology and the other was a CIPP technology. Each demonstration report includes: extensive documentation of technology design considerations; QA/QC procedures; required preparation, installation, and cleanup activities; evaluation of technology performance through post-installation field and laboratory testing; and evaluation of technology cost and on-site carbon footprint (EPA 2012a, b, c). The results of this U.S. EPA program highlighted the value of demonstrating and evaluating emerging technologies so that each new technology's capabilities and applicability can be independently studied (Matthews *et al.* 2014).

Spray-on polymeric lining

The use of polymeric spray-on linings has potential as a cost-effective means of rehabilitation in water distribution as an alternative to cement mortar lining (CML), which has been used for more than 50 years. These organic polymer materials combine a resin and a hardening agent to form a fast curing thermoset material with a cross-linked molecular composition. The evaluated polyurea product was made from a 1:1 by volume blend of two components (a base component that is a white thixotropic liquid and an activator component that is a black thixotropic liquid) and when combined and cured it resulted in a lining with a gray finish. The product was designed to a tensile strength of 16 MPa per ASTM D638, a flexural strength of 22 MPa and flexural modulus of 720 MPa per ASTM D790. The lining was designed for use in water main rehabilitation applications of 4 to 12 in. (100 to 300 mm) pipe for lining runs up to 500 ft (150 m). Straight runs are preferred, but bends of up to 22.5° are feasible and tees can be lined through although active valves cannot. Typically, pits are excavated at valve locations and the lining is performed from the pit. The lining was also meant to minimize the blockage of service connections, which eliminates the need to use open cut service line reconnections.

The unlined, spun CI test pipe was 1,342 ft (409 m) long and had an inner diameter (ID) of 10 in. (250 mm), a burial depth of 4 ft (1.2 m) below ground surface, and operated at pressures between 85 and 90 psi (585 and 620 kPa), while transmitting approximately 1.75 million gallons per day, mgd (6.62 megaliters per day) of flow. The test pipe was cleaned per the installer's needs and the lining was applied over the course of 4 days. Hydraulic testing of the lined pipe section the following week showed flow rates had decreased from 1,300 gallons per minute, gpm (5,900 liter per minute, lpm) to 200 gpm (900 lpm) in both directions. This prompted an investigation that revealed significant portions of the liner had collapsed and other areas contained blisters and cracks (Figure 1), which were not present during the post-lining CCTV. Subsequent to the failure discovery, the entire test pipe was abandoned in place and a new 12 in. (300 mm) DI pipe was installed.

The failure discovery was important in helping to identify material formulation issues and subsequent analysis of the potential causes of the failure indicated that moisture

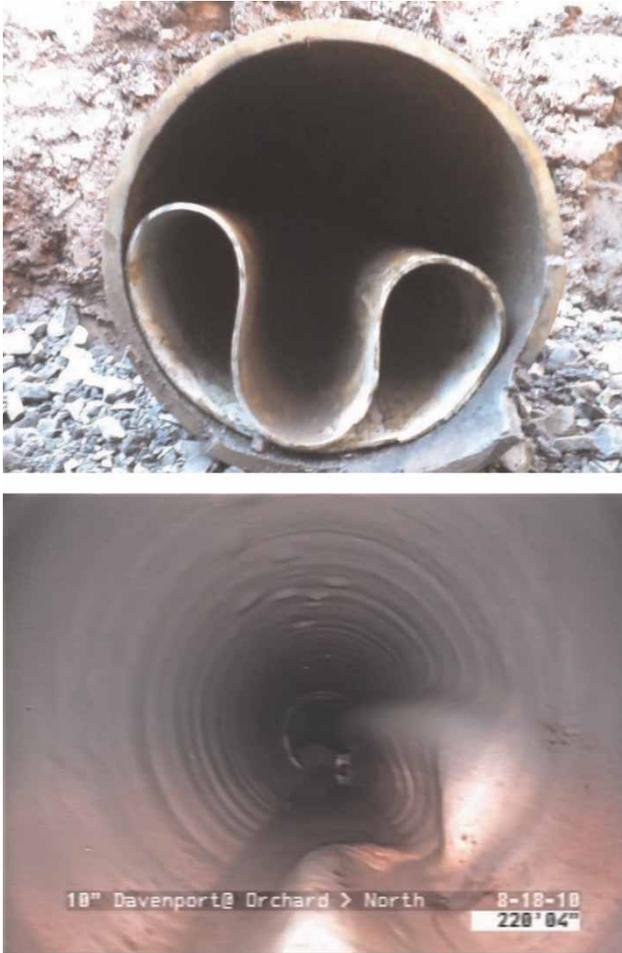


Figure 1 | Collapsed liner (top) and two folds and blisters (bottom) inside the pipe.

conditions (previously not experienced in product development and use) prevented a proper chemical reaction from occurring, which greatly reduced the material properties, resulting in a lining collapse. Ultimately, the liner failure had a positive effect in the industry by revealing that the polymeric material was not robust enough to use in typical *in situ* water main conditions leading to the removal of the product from the market to allow for further development (Matthews *et al.* 2012a).

Cured-in-place pipe

The CIPP liner demonstrated for this project consisted of two woven seamless polyester jackets, of which the inner jacket has a polymeric membrane bonded to the interior to ensure water tightness. The liner was impregnated at

the work site in a purpose-built vehicle where the resin was injected between the jackets and distributed by feeding the liner through a nip roller. The liner was designed and tested in accordance with the procedures set out in ASTM F1216 and physical properties are determined in accordance with ASTM F1216 (ASTM 2009). The liner was installed according to ASTM F1743 (ASTM 2008a).

The liner is available in diameters of 6, 8, 10, and 12 in. (150, 200, 250, and 300 mm) and has an operating pressure capability of up to 150 psi (1,034 kPa). The internal polyurethane coating provides for a Hazen–Williams friction coefficient (C) greater than 120. The CIPP liner can be installed in lengths up to 500 feet (152 m) between access pits and it is installed by pulling the liner in place and pushing a pig through the liner using water pressure to form the liner to the pipe wall. Circulating hot water for 90 minutes and then holding under pressure for up to 12 hours completes the curing process. The service connections are reinstated from within using a remote controlled mechanical robot to cut open the taps, with 5% of the services typically requiring external reinstatement due to difficult conditions. The liner design service life is estimated to be 50 years based on calculations from ASTM F1216 and based on the material properties and design, the product is fully structural and capable of withstanding all dead and live loads, and internal pressures, including vacuum, without the help of the strength of the existing pipe.

The unlined, CI test pipe was 2,040 ft (622 m) long and had an ID of 6 in. (150 mm), a burial depth of 6 ft (1.8 m) below ground surface, and operated at pressures of 60 psi (414 kPa), while transmitting approximately 0.86 million gallons per day, mgd (3.26 megaliters per day) of flow. The demonstration, which took place over the course of 2 weeks, was successful, but continued improvements should be made in the process for internal reinstatement of services (Matthews *et al.* 2012b). Based on this evaluation, Columbus, Ohio Department of Public Utilities Division of Water became interested in CIPP lining for water main rehabilitation projects (Pyzoha 2013).

CONCLUSIONS

This paper provides a summary of the efforts by the U.S. EPA to assist municipalities and water utilities in the renewal of water

distribution and wastewater collection systems in the USA. The outputs from this research are shared with stakeholders through the publication of reports and demonstration project results on the U.S. EPA's Aging Water Infrastructure Research Program Web page available at www.epa.gov/awi. The primary contribution of this paper is the state-of-the-art review of current and emerging renewal technologies used for the repair, rehabilitation, and replacement of water distribution and wastewater collection systems. This paper also discussed the results of other program components which are intended to aid in the use of the renewal methods. These components included: the CIPP retrospective evaluation study; field demonstration of innovative and emerging water rehabilitation technologies; a review of QA/QC measures for trenchless rehabilitation technologies; and current decision-making models and methodologies available to support rehabilitation versus replacement decisions were discussed.

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