CONSTRUCTION TECHNOLOGIES FOR SEWER REHABILITATION

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ABSTRACT: The deterioration, inadequacy, and insufficiency of the nation's infrastructure is a serious problem affecting the U.S. today. Several important organizations have documented this problem extensively, and agreed on the need to develop new infrastructure rehabilitation research strategies, tools, and products to improve the performance and efficiency of existing facilities. Since the inherently complex nature of rehabilitation projects requires very close interaction between the design and the construction processes, an understanding of the characteristics, requirements, capabilities, and limitations of construction technologies for infrastructure rehabilitation is important to help overcome the fragmentation of the planning, design, construction, and maintenance processes, and the conservative approaches of designers that focus more on legal and liability concerns than on innovation and development of new ideas and technologies. It is also important to understand the role construction technologies play in developing solutions for infrastructure rehabilitation problems. Focusing on the rehabilitation of sewer systems as an example, this paper: (1) Presents a synthesis of the state of the art of construction technologies for sewer rehabilitation; (2) discusses the role they play within an optimal planning approach for sewer rehabilitation; and (3) introduces a broader framework for an integrated design/construction research program for infrastructure rehabilitation.

INTRODUCTION

The deterioration, inadequacy, and insufficiency of the nation's infrastructure is a serious problem affecting the U.S. today. Several important organizations have documented this problem extensively, and provided specific recommendations for research. For example, the state of the urban infrastructure in the U.S. was the focus of the recent National Science Foundation (NSF) report of the Civil Infrastructure Systems Task Group ("Civil" 1993). In this report, the task group agreed that the civil urban infrastructure has not been properly maintained to meet present society needs. The task group also identified important barriers that currently preclude U.S. civil infrastructure systems (e.g., electric power, gas and liquid fuels, telecommunications, transportation, and water and sewer systems) from benefiting from advances made in emerging technologies: the current technology transfer process, the complexity of civil infrastructure systems, economic constraints, and the specter of legal and liability concerns. Furthermore, the task group recommended a research strategy to address the rehabilitation of civil urban infrastructure through the application of a holistic systems approach that includes issues of system behavior, deteriora-

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tion, assessment, and renewal. A fundamental component of this strategy is the development of new scientific and engineering knowledge in parallel with the implementation of existing knowledge. However, the report highlighted the lack of acceptance of new technologies to solve the existing problems, citing as reasons the constraints imposed by the complexity of the urban infrastructure system, and the attitudes of design professionals who are not comfortable with these new technologies.

The National Council on Public Works Improvement (NCPWI), created as a result of the Public Works Improvement Act of 1984, also found convincing evidence that the quality of America's infrastructure is barely adequate to fulfill current requirements, and is insufficient to meet the demands of future economic growth and development (Giglio et al. 1988). Among the tactics used in developing a strategy to upgrade America's infrastructure, the NCPWI recommended the development of steps to improve the performance and efficiency of existing facilities, and the establishment of strong incentives to ensure adequate maintenance and, where appropriate, adopt new technologies.

Finally, in a report, the Civil Engineering Research Foundation (CERF) identified the revitalization of the public works infrastructure as the first of their five research thrust areas (Civil 1991). This thrust area discussed the need to improve the U.S. infrastructure deficit through investments in research and innovation; the need for more planning, analysis, and operational tools to assist managers with technical and financial decision making; and the need for new methods, materials, and techniques to repair, rehabilitate, and renovate the existing infrastructure.

An analysis of these recommendations shows a consensus on the need to develop new infrastructure rehabilitation research strategies, tools, and products to improve the performance and efficiency of existing facilities. One of the biggest obstacles to achieving this stems from the inherently complex nature of rehabilitation projects that requires very close interaction between the design and the construction processes, i.e., the design solution to a given project requires integral and early definition of construction technologies, operations and methods. This interaction is often not possible because of: (1) Institutional barriers (e.g., legislation, contractual approaches), which support the traditional design-bid-build approach to construction; (2) conservative approaches that focus more on legal and liability concerns than on innovation and development of new ideas and technologies; and (3) the fragmentation of the planning, design, construction, and maintenance processes into independent pieces that focus on the optimization of individual components rather than on the optimization of the complete system.

Thus, to overcome these obstacles, it is necessary to develop new mechanisms for:

- Project delivery.
- The development, testing, validation, and acceptance of new construction technologies for rehabilitation.
- A closer integration between designers and constructors for the development of solutions for infrastructure rehabilitation problems.

A starting point to achieve this is a clear understanding of the characteristics, requirements, capabilities, and limitations of construction technologies for infrastructure rehabilitation, and the role they play in developing solutions for infrastructure rehabilitation problems. Focusing on the rehabilitation of sewer systems as an example, this paper: (1) Presents a synthesis of the state of the art of construction technologies for sewer rehabilitation; (2) discusses the role they play within an optimal planning approach for sewer rehabilitation; and (3) introduces a broader framework for an integrated design/construction research program for infrastructure rehabilitation.

PROBLEM OF SEWER SYSTEM REHABILITATION

The condition of the sewer systems in the U.S. is representative of the urban infrastructure in general. Aging becomes self evident when it is considered that a number of the oldest cities in the U.S. have operating sewer collection systems that are more than 100 yr old. Systems this old cannot hide the rigors of time. St. Louis, as an example, has combined sewers (collecting storm water and sewage) that are more than 125 yr old. In 1981 alone, this city had 4,000 sewer collapses and an astronomical repair bill (Weil 1990).

Signs of wear for underground infrastructure like sewer collection systems are not usually apparent until the damage is done. This leads to a lack of routine maintenance actions, unless or until there is a failure. According to the Department of Housing and Urban Development (1984), "Most of the community sees only the inevitable results of prolonged neglect, such as cracked pavement, collapsed streets, backed-up sewers."

Pipelines represent the largest capital investment made by most sewerage undertakings and yet, the conditions of these buried assets used to be generally unknown until the recent past. The reason is that 95% of the sewer system is too small for effective manual inspection (Water 1983). Hence, until the appearance of closed-circuit TV (CCTV) sewer inspections in the 1960s, the condition of most of the sewer system was little known. The use of CCTV and other modern inspection techniques brought to light the poor state of the system.

The maintenance, repair, and rehabilitation of the sewer system infrastructure is no trivial task. In fact, sewerage systems form one of the six most capital intensive infrastructure systems; the other five are: schools, roads, water, storm drainage, and solid waste disposal (Frank and Falconer 1990). Although there is no consensus regarding the magnitude of the problem, several authors provide impressive figures. For example, Thomson (1991) gives a rough estimate of the magnitude of the work needed to keep the systems in good conditions. He concludes that by giving an average life of 100 yr for a typical line, the U.S. should renew about 6,000 mi of pipe yearly (a $2.5 billion job). In turn, Delleur (1989) cites a report of the Associated General Contractors of America (*America's* 1983), that identified a $169.4 billion need for drainage and minor flood control over a 30-yr period. This would give a $5.64 billion annual expenditure that is roughly twice Thomson's rough estimate, although it should be noted that the AGC figure includes other items apart from the actual rehabilitation of the lines in the system. Finally, another approximate figure is given by Grigg (1984). The figure is $185 billion for the storm-water class (including combined sewer systems).

The problem of sewer rehabilitation is further compounded by two critical challenges. The first challenge is that most rehabilitation work has to be done in heavily developed areas. While simply digging and replacing the old pipe is still the best (or only) option in many cases, it is usually highly

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disruptive and expensive. Thus, there is a need and a strong incentive to find alternative rehabilitation technologies that make use of existing pipes, and that provide solutions with minimum disruption, while maintaining cost-effectiveness.

The second challenge is that most of the work is done as a response to crises that require immediate solutions, rather than planned efforts that develop optimal solutions. This problem is schematically shown in Fig. 1. In this framework, departments of public works react to a given crisis with a sewer-rehabilitation project that is handled by either the division of design or by the maintenance division, depending on the nature and urgency of the crisis, within existing standards, codes, and regulations. These divisions, in turn, develop a design solution either with their in-house design staff, or through the use of external design consultants. In both cases, the design solution is issued for bids, and once awarded, the selected construction company provides the final construction solution.

Throughout this process, the benefits that the application of new construction technologies for sewer rehabilitation may bring to a project are never quite fully realized. First, standards, codes, and regulations are slow in incorporating new technologies. Second, designers not only cannot use new technologies if they have not been incorporated within these standards, codes, and regulations, but even if they have been, they are many times reluctant to adopt or try them if they are not familiar with them or have not tried them before. Finally, the lack of mechanisms to integrate con-

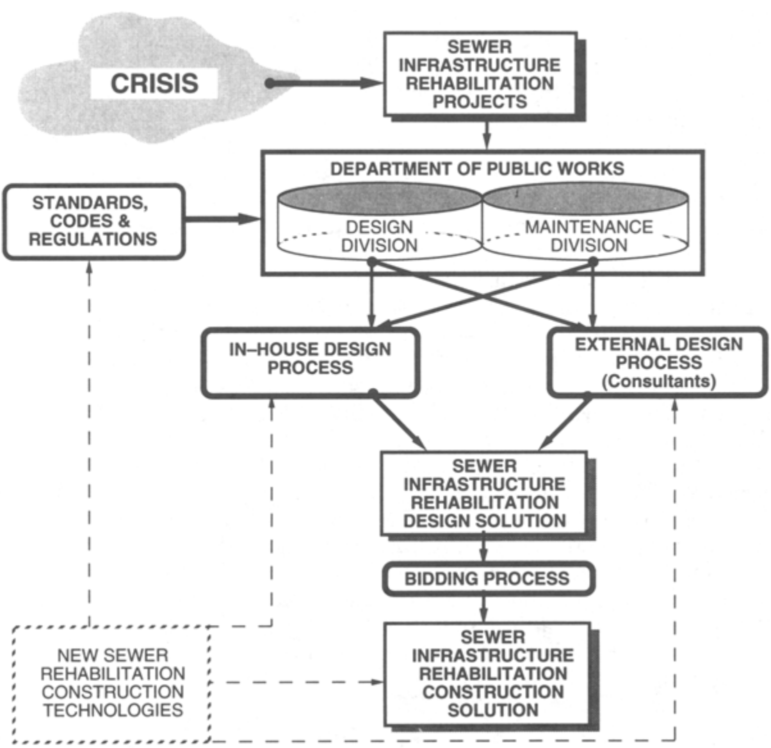

FIG. 1. Crisis-Based Sewer Rehabilitation Approach

struction input into the design process, precludes designers from learning more about these technologies, and leaves constructors limited to the options specified in the design solution.

This situation becomes especially troubling, since a number of new and emerging technologies are currently available, which enable total rebuilding of a sewer system without excavation, including: rehabilitation of collectors, drain lines, manholes, service laterals, and mains (Osborn 1990). These new advances are capable of reconstructing laterals from inside mains to and beyound the property lines, structural rebuilding of existing manholes, and relining of manholes without leaving any annular space.

This paper will present next, a state-of-the-art review of the main sewer-rehabilitation construction technologies. However, due to length limitations, this paper concentrates primarily on technologies for rehabilitation of sewer mains, which form the primary component of a sewer-collection system. Also, except for a brief introduction, trenchless technologies have been excluded because it is now a separate, full-fledged topic in itself. The sewer-rehabilitation technologies discussed can be divided into four major divisions: stabilization, linings, coatings, and excavation and replacement. A brief summary of these technologies is given in Table 1. Each of these technologies is explained next.

STABILIZATION TECHNOLOGIES

Stabilization methods are used in cases where otherwise structurally sound and physically intact sewer pipes face problems of mortar deterioration and/or excessive infiltration through joints or cracks. The two major ways to overcome these problems are pointing and chemical grouting.

Pointing

Pointing can be done either manually or using pressure equipment. The first method involves the placing and trowelling of mortar at the point by hand while the second uses a flexible hose, connected to outside equipment, for the application of a premixed mortar. The use of this method is restricted to large diameter pipes capable of man entry.

Pointing methods are applicable to structurally sound brickwork and masonry rubble sewers. They present an ideal opportunity for automation and have already been automated by some. Their particular advantage lies in their low cost, minimal disruption, and increased hydraulic efficiency due to smoother joints. They, however, need flow diversion, a thorough cleaning and infiltration control before any repairs can be carried out. Futhermore, the pointing methods are time-consuming and labor-intensive, and quality control is difficult.

Chemical Grouting

This is an extensively used method that uses gel grouts to seal leaks in joints and cracks. In large, man-entry sewers, this is done by pumping grout in pulses, through cracks until an acceptable back pressure is obtained. In smaller pipes a cylindrical packer with inflatable collars at the ends is used. The collars are inflated and the joint tested for failure. If leakage does occur, grout is pumped until acceptable back pressure is achieved. Grouting needs some preparation before application. This essentially consists of root treatment using herbicide, root removal, and cleaning of the entire pipeline reach.

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TABLE 1.

Rehabilitation Methods			Principal Characteristics						
Method (1)	Category (2)	Subcategory (3)	Improvement (4)	Entrance (5)	Diameter range (cm) (6)	Lateral connections (7)	Shapes (8)	Curve negotiation (9)	Time (10)
(*a*) Stabilization									
Pointing	—[a]	—[a]	Hydraulic	Man and nonman entry	>45	—[c]	Various	Good	Days
Grouting	—[a]	—[a]	Hydraulic	Man and nonman entry	15–300	—[c]	Circular	Limited	Hours
(*b*) Linings									
Pipe linings	Slip lining	Glass-reinforced plastic pipes	Hydraulic	Man and nonman entry	30–240	No	Various	Limited	Hours
		Polyolefin pipes	—[b]	Man and nonman entry	15–60	Yes	Circular	Limited	Hours
		Ductile iron pipes	Structural	Man and nonman entry	10–150	—[b]	Circular	—[b]	—[b]
	Cured-in-place pipes	—[a]	Hydraulic and structural	Man and nonman entry	15–240	Yes	Various	Good	Hours
	Modified slip lining	—[a]	Hydraulic	Man and nonman entry	10–37.5	Yes	Various	Good	—[b]
	Spiral wound pipes	—[a]	—[b]	*Man and nonman entry*	7.5–90	—[b]	Various	Limited	—[b]
Segmental linings	Glass-reinforced cement pipes	—[a]	Hydraulic	Man entry	>120	Yes	Various	Good	—[b]
	Glass-reinforced plastic pipes	—[a]	Hydraulic	Man and nonman entry	30–240	No	Various	Limited	Hours
	Resin concrete pipes	—[a]	Hydraulic	Man entry	>75	Yes	Various	—[b]	—[b]
	Precast gunite	—[a]	*Hydraulic and structural*	*Man entry*	>90	Yes	Various	—[b]	—[b]
(*c*) Coatings									
Cement mortar coatings	—[a]	—[a]	Hydraulic and structural	—[b]	>20	Yes	Various	Limited	—[b]
Reinforced gunite	—[a]	—[a]	Hydraulic and structual	Man entry	>90	—[c]	Various	Good	Days
Resin coatings	—[a]	—[a]	Hydraulic	Nonman entry	7.5–45	Yes	—[b]	—[b]	Hours

[a]No categories and/or subcategories.
[b]Not available.
[c]Not applicable.

The gel grout when uncured is low in viscosity and, therefore, able to move easily into the cracks and joints and the surrounding soil as well, thus forming an impermeable seal. The amount of grout used depends on the degree of surrounding soil permeability and the size of voids present. Foam grouts are also used, especially in cases where large voids exist outside the pipe because they do not penetrate outside the cracks. Instead, they form an in-place pipeline gasket of rubberlike material which is both tough and flexible. The major gel and foam grouts in use today include acrylamide gel, acrylate gel, urethane gel, and polyurethane foam. Some of them have recently been classified as toxic and their use stopped or limited—the most significant casualty has been acrylamide, which had become the major grouting product.

Chemical grouting can be performed in both man-entry and nonman-entry structurally sound sewer pipes and cures both leaking joints as well as circumferential cracks. It causes minimal disruption, takes a short time, tolerates low flows during application, offers good corrosion resistance, and is very inexpensive. A major limitation lies in the nonapplicability to non-circular and irregular sections. The ability to negotiate bends is also limited. Moreover, grouting loses its water tightness if it gets dried due to the lowering of the water table. Grouting may not be the perfect solution but due to its cheap cost and the good chance of success it offers, this method must always be considered a possible option.

There is another variation of the stabilization methods that may be mentioned here. It is called Weko-seals and utilizes stainless-steel and ethylene propylene (EP) based rubber for joint rehabilitation. These seals are suitable to a wide range of diameters: 35–345 cm (14–138 in.). They also offer good corrosion resistance characteristics and possess the ability to negotiate bends as well. The use of Weko-seals has been quite extensive (Stalnaker 1992).

LINING TECHNOLOGIES

In contrast to stabilization methods that do not provide structural improvement, lining techniques can be used to improve both the hydraulic capacities of a sewer system and its structural integrity. In addition, they also provide increased abrasion and chemical resistance to the internal surface of the pipes. To simplify the discussion, lining techniques can primarily be divided into two major categories on the basis of linings used: pipe linings and segmental linings.

Pipe Linings

This process involves insertion of pipe linings inside the affected sewer in order to restore integrity. This can be done either in short segments (segmented) or in continuous lengths (standard) and the pipe inserted can be flexible or rigid. The application is not limited to circular sections alone; the only shortcoming is that the smallest section in the line determines the maximum pipe size that can be installed. This limitation is often overcome by removing some of the smaller sections. Some slip-lining methods require bypass pumping for installation.

Slip Lining

Slip lining is one of the more widely used lining techniques and is capable of dealing with most of the structural deterioration problems, excepting of course the crushed pipe scenario. They possess excellent corrosion resistance

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as well. A slight reduction in hydraulic capacity does, however, take place. Moreover, slip-lining techniques are unable to negotiate bends or to accommodate trenched service connections.

Three major steps are involved in the slip-lining process. First, the problem areas and location of service connections are identified by a walk through the system or through CCTV. Next, the system is washed clean of roots and other solids and protrusions. Third, the pipe is pushed or pulled into place. Pushing is done either through backhoe or a jacking system whereas pulling is carried out by means of a winch and pulley system and, therefore, requires special, strong joints to bear the considerable traction forces.

Among the several types used for this purpose, three stand out for wide use and stability:

- Glass reinforced plastic pipes (GRP). These pipes are specially suitable for use in man-entry sewers, including noncircular sections. GRP is a resin-based material, reinforced with glass fiber and sand to act as aggregate and filler, respectively. GRP pipes have a high strength/weight ratio and are available in a variety of cross sections. They sometimes require temporary support during grouting. According to Stalnaker (1992), tests have revealed an extremely long expected design life, greater than 100 years, for segmented joint (Hobas) slip lining. Moreover, they have been found to have excellent corrosion resistance and a capacity to negotiate large radius curves. They are available in diameters of 36–240 cm (12–96 in.), and no upper limit exists for the reaches to be installed. The condition of the pipes and the curves to be dealt are limitations. Quick insertion times are possible.
- Polyolefin pipes (POP). These pipes are available in many forms, differentiated on the basis of strength, stability with temperatures, and maximum avaiable diameter and length. They range in diameter from 15 to 60 cm (6–24 in.), possess excellent corrosion resistance, and have a design life of 50 yr. The lengths are joined together either through the butt-fusion welding system that is carried out on the surface or in an enlarged trench, or through screw-jointed systems that utilize short lengths and allow access via manholes. The latter are relatively more cost-effective for short and deep lengths. The joints are made watertight using sealant mastic. POP are able to negotiate large radius curves and allow quick insertion (hours only). Their use is, however, limited to circular cross sections, and a relatively high loss of cross section takes place. In addition, grouting of the annulus is required and there is flotation during grouting.
- Ductile iron pipes. These pipes have proved to be a very strong and reliable form of pipe lining except in corrosive atmospheres. They significantly increase the existing pipe strength and make the need for filling the annular space between the new and existing pipes redundant. They can be placed in much longer reaches and can overcome obstructions and friction much more easily because of their ability to bear large pushing forces. However, they are limited to circular cross sections, can cause significant loss of cross section, and can often prove to be costly.

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To overcome one of the main shortcomings of slip lining, i.e., the definition of the section by the smallest pipe in the reach being lined, several commercial systems have come up recently that use reinforced thermosetting resin pipes (RTR). These pipes work either by producing a temporary reduction in the diameter of a polyethylene pipe in order to insert it into the existing segment (deformed pipe and fold and form pipe system) or by making use of a fiber tube impregnated with resin that may be easily inserted into the existing conduit and later formed and cured in place.

Slip lining has proved to be a great success in actual practice. Ainsworth (1989) describes the use of a polyvinyl chloride (PVC) pipe that was pulled inside a 35-cm (14-in.) pipe for lengths that were up to 600 m (2,000 ft). In this operation, which was performed for the sewer system of June Lake, Calif., a heat-fusion machine was used that formed a joint stronger than the pipe itself. Goodenough and Smith (1991) cite the use of high density polyethylene (HDPE) slip lining for an extensive rehabilitation work in Santa Barbara, Calif. HDPE was utilized for the major part of the Albuquerque sewer rehabilitation program (Pena and Holstad 1989). Stalnaker (1992) also mentions another form of HDPE slip lining, segmented joint (Spirolite), which has a diameter availability in the range of 60–300 cm (24–120 in.), and curve negotiation, corrosion, and design life characteristics quite similar to others just mentioned. Two other examples are Vip-Liner and Duratron.

Cured-in-Place Pipes

Cured-in-place (CIP) pipes overcome the limitations imposed by the slip-lining techniques, which are usually constrained by the smallest section of the system. Moreover, in contrast to slip lining, CIP pipes face no problem in negotiating bends; bypass pumping is, however, required during installation. Insituform is one of the more well-known commercial forms of CIP pipe systems. It is also known as resin-impregnated fabric inversion lining. The process involves primarily the insertion of a flexible lining into the sewer, utilizing an inversion process with in situ curing. It has a very wide application range and can be used in noncollapsed man-entry as well as nonman-entry pipes, of any cross section and diameters from 20 to 180 cm (8–72 in.). It also works well on pipes with minor deformations.

The lining consists of a polyester needle felt bag, impregnated with a thermosetting polyester or epoxy resin. The fabric thickness in the tube is determined by standard buried flexible pipeline equations and can be increased simply by adding layers of polyester felt in increments of 1.5 mm. A final skin of polyurethane is bonded to the felt to prevent washout of resin and to contain the water used for inversion and curing. This membrane, about 0.25-mm thick, later forms the inner surface of the cured lining. The lining is impregnated with resin in the factory and transported for installation, generally within one day.

The section is cleaned and all flow diverted before the insertion. The insertion is done via manholes under pressure of a column of water and curing is done by circulating hot water or even hot air. During insertion some resin migrates into the joints and cracks, thus locking the CIP pipes into place once the curing occurs. The ends are cut and sealed and service connections reestablished by locating their presence from dimples caused in the lining. This is done utilizing CCTV, which is also used to guide equipment for cutting the line at the required points.

The primary advantage of Insituform lies in the minimum disruption it

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causes and its rapid installation; up to 150 m (500 ft) in 18 hr in some cases. Moreover, there is no reduction in capacity, which could in fact be increased due to improved hydraulics. The resistance to corrosion is also high. Insituform has now been in use in the U.S. for almost 17 yrs. During this period more than 2,400,000 m (8,000,000 ft) of pipelines have been treated this way, making it perhaps the most used rehabilitation technique. Its high cost due to patents and lack of competition, however, excludes it from ordinary projects. Among many authors who describe the successful application of Insituform, Bible (1992) describes the use of Insituform in Nashville, Tenn., where problems of infiltration/inflow had become so severe that a moratorium in sewer connections had to be placed until the system was rehabilitated.

Force main reconstruction has also been accomplished using CIP pipe methods and the newly developed end-seal technology. Osborn (1990) describes the procedure as involving the creation of an annular space at the point where CIP pipes terminate. An O-ring followed by a spacer is inserted into this space and the end dressed with a grouting material. A highly engineered end seal is thus obtained, which prevents tracking and allows the termination of CIP pipes without leaking.

There are various other commercial forms available in the realm of CIP pipe technology:

- Ozite Corp. possesses a structural reinforcement method, also based on a resin-impregnated fabric. This fabric is pulled inside the deteriorated pipe and then inflated with a bladder that forces the resin-soaked liner against the pipe walls, and bonds it to the wall (*Public works manual* 1992).
- Another system, known as Pipeline Automated Lining Process (PALTEM), is owned by the Max Foote Construction Company. It consists of a fiber tube impregnated with an approved resin that is inserted into an existing pipe and cured with heat. It is suitable for a diameter range of 15–45 cm (6–18 in.), possesses excellent corrosion resistance characteristics, and takes little time for installation. PALTEM is covered by ASTM F1216 (*Specification* 1992).
- The Environmental Protection Agency (EPA) (Environmental 1991) describes another system known as KM-Inliner, which was initially developed in Germany by the Kanal Mueller Gruppe and introduced in the United States not long ago. The material used is polyester resin impregnated felt, although vinyl ester resin is also sometimes used. The diameters covered are 15–120 cm (6–48 in.).
- Another brand is Campozitex (Stalnaker 1992), which utilizes an epoxy resin impregnated fabric, suitable for diameters of 20–45 cm (8–18 in.).

Modified Slip Lining

Modified slip lining is an improvement upon the conventional slip-lining process. U-Liner is one of its most well-known forms. It is an extensively used methodology. More than 60,000 m (200,000 ft) of pipelines has been treated with U-Liner within just 4 yr of its introduction (Stalnaker 1992). The process is explained in a commercial brochure, "U-Liner the Better Way." It consists of extruding HDPE in a round form and then deforming and spooling the U-Liner in designated outside diameters, schedules, and lengths. The condition of the pipeline is measured and recorded before insertion by means of CCTV. The U-Liner is then transported and inserted in the old pipe using either the pushing or the pulling technique. Immediately after insertion, inflation is carried out using a combination of pressure and hot water and the U-Liner made to conform with the pipe's internal surface. Once the installation of the liner is complete, the connecting lines are reconnected by external tapping or alternately, through a remote cutting device.

The U-Liner has a diameter range of 10–37.5 cm (4–15 in.). It has very good corrosion resistance characteristics, a design life of 50 yr, minimum disruption, and a short insertion time in the range of hours. It has the ability to negotiate bends, though in a restricted manner; short 22.5° bends and long, sweeping 45° bends. Like Insituform, with which it shares some of its characteristics, the process is patented and monopolized and, therefore, expensive. U-Liner, like the other modified slip-lining (formed in place) methods, requires diversion of flows for installation.

With the continuing developments in this field, other methods that involve modified slip lining have also appeared. Swagelining is one of them (*Public works manual* 1992). Like U-Liner, Swagelining also uses the principle of reduction of section before its introduction into the pipe; the original shape is then recovered later. In this process, which was first developed and used by Dowell Schlumberger Inc., a polyethylene pipe is heated in a special die to reduce its diameter, and then it is winched through the pipe to be rehabilitated. As the polyethylene pipe cools, it expands and regains its former shape, filling the inside of the deteriorated pipe and leaving no annular space. Swagelining was used during the sewer-system rehabilitation of Wheaton, Ill. The advantages it was found to have over the two other alternatives, Insituform and Open Cut, were its lower price and acceptance by the Illinois EPA. It also met the ASTM standards, in contrast to Insituform (Murzyn 1990).

NuPipe is another commercial process. It involves the insertion of a preheated, folded PVC pipe into the affected pipe. The inserted pipe is then further heated and progressively expanded against the interior surface of the host pipe. The finished pipe extends over the installation length in a continuous, tight-fitting, watertight pipe-within-a-pipe manner. NASSCO (*Specification* 1992) and EPA (Environmental 1991) describe another commercial process, RePipe, a similar lining process that applies the fold and form technique to a polyvinyl chloride (PVC) pipe. Danby, which utilizes PVC as a material is yet another formed-in-place methodology. It is available in diameters 10 in. and up—and those greater than 36 in. also possess the ability to negotiate bends. The insertion time, though short, varies with the method of installation adopted: Winding process can install at the rate of 90 cm/min (3 ft/min) while in man-entry sewers rates of 21 to 30 m/day (70–100 ft/day) per crew can be achieved (Stalnaker 1992).

Spiral Wound Pipe

The application of Spiral Wound Pipe is explained by McAlpine (1991) and NASSCO (*Specification* 1992). The process involves the installation of a helically wound two-part unplasticized/rigid polyvinyl chloride (uPVC) strip that forms a liner in the existing sewer line. A winding machine, placed down the manhole and aligned with the existing sewer line, is used to form the liner. The two strips of PVC material are fed into a tube shape, locked, and joined together. Then, they are fed forward into the existing pipe until

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reaching the next manhole. The liner must be made of compounds specified for the PVC pipe extrusion suitable for potable water and drain/waste/vent.

This method is similar to the standard sliplining and is advantageous in that no trenches are required at the manholes. However, it can only be used with pipes of regular cross section, having no obstructions, and possessing little or no change in alignment.

Segmental Linings

Segmental linings are made up of different pipe pieces connected together at longitudinal joints. They are suitable for man-entry sewers and available in a variety of shapes. The segments are entered through existing manholes or through shafts made for this purpose. Segmental linings are available in a variety of materials. Some of them are glass-reinforced cement (GRC), glass reinforced plastic (GRP), resin concrete, and precast gunite. Steel linings have also been used successfully.

Glass-Reinforced Cement

GRC has a high strength/weight ratio and is capable of resisting chemically aggressive and abrasion causing flows. This lining is applicable to structurally sound sewers greater than 1.2 m (4 ft) in size and a variety of shapes. Jointing is done both radially and longitudinally using lap joints or by means of tongue and groove joints. The lap joints may be screwed or nailed together, using an impact nail gun, to prevent grout ingress. The segmented linings are anchored and after being finally assembled, made to undergo cement pressure grouting. The large number of pieces to be erected and jointed does make this method somewhat labor-intensive.

Glass-Reinforced Plastic

GRP is manufactured from fiberglass and a choice of resins from polyester to vinylester. It is applicable to structurally sound man entry sewers and is capable of bearing chemically aggressive and sediment carrying flows. It has a high strength/weight ratio and is available for a variety of cross sections. After the cleaning of pipe, the lightweight lining segments are installed in place. Longitudinal joints are made in the form of lapped, tongue and groove, or loose collar. The space between the liner and the pipe is grouted with cement. Epoxy sealants are used to prevent the ingress of grout into the pipe, thus creating a smooth, uniform interior and, therefore, excellent hydraulic characteristics. In this case, too, the jointing process is highly labor-intensive.

Resin Concrete

Polyester resin concrete is made up of a mixture of aggregates and polyester resin. The segments thus obtained are very hard, heavy, and brittle, though with a smooth internal and a rough external surface. They are available in a variety of cross sections but are applicable to larger-size sewers only. They are capable of resisting chemically aggressive flows. The segments are placed in position and connected together with simply lap joints. The annular space is filled with grout. Joint surfaces are coated with an epoxy mortar to prevent grout ingress. The jointing process is labor-intensive.

Precast Gunite

Gunite segments are dense, heavy, and strong, and provide a smooth internal surface. The exterior surface is kept rough for good bonding with annular grout. They are suitable only for larger man-entry pipes. Gunite brings increased structural strength to the system as well. Both the lining thickness and the steel reinforcement can be altered to different structural requirements. The mesh typically used as reinforcement is 100 × 100 × 3.6 mm.

COATING TECHNOLOGIES

Coatings are used to extend the life of an existing sewer by increasing its strength and protecting the existing material from corrosion or abrasion. Hydraulic capacities may also be improved by this manner. Some of the primary coating techniques are cement mortar coating, reinforced gunite, and resin-impregnated coating.

Cement Mortar Coatings

Cement mortar coatings can be applied, with minimum of disruption, to concrete, steel, and iron pipes. The structural integrity and flow criteria are greatly improved with the result that the pipeline's life is extended by as much as 30–50 years. Suitability extends to a large variety of cross sections and diameters 20 cm (8 in.) and larger. Applicability is limited by a large number of bends in the system or very cold temperatures.

To apply the mortar, the pipe is first cleaned using one of the three methods available: hydraulic cleaning, mechanical or drag cleaning, and hand cleaning. Then after dewatering the pipe, the mortar is applied to the wall surfaces using the centrifugal or mandrel process using one part of sulphate-resistant cement to two parts of sand. The centrifugal process involves the use of a lining machine with a revolving, mortar-dispensing head and trowels in the back to smooth the mortar immediately after application. On the other hand, the mandrel process utilizes a pressure-extrusion technique that causes the mortar to be forced over the conical mandrel against the well.

Cooper and Heitzman (1992) have discussed the use of Silicote Lining, a new technique that is essentially the same as cement mortar lining but uses a much faster curing concrete than conventional portland cement.

Reinforced Gunite

Also known as reinforced shotcrete, this is a mixture of cement, sand, and water applied by pressure with a gun on a cage of reinforcing steel previously fixed to the existing sewer wall. Reinforced gunite can solve structural problems as well and is applicable to both varying and nonvarying sections. However, it is limited to man-entry sewers and requires long and complete shut off of the system. Futhermore, infiltration needs to be controlled in order to ensure proper bonding. The operation is difficult to supervise and highly dependent on the operator's skills. Zurawski (1992) describes the use of shotcrete to repair and rehabilitate brick sewers. He finds shotcreting to be a highly practical method and shotcrete to be an excellent structural material capable of developing a strong bond with old concrete, brick, and other masonry surfaces.

Resin Coatings

Resin coatings utilize nonsolvented hybrid polyurethane resins or phenolic epoxies. They are applicable in cases where corrosion or erosion problems exist. They have good adhesion to both concrete as well as steel pipes, cure rapidly, and possess high impermeability. However, being a relatively recent introduction the resin coatings, they have yet to withstand the test of time.

A variation is available by the name of Trace-Taline Relining System, which is owned by Reline America Inc. This method uses a compressed-air–driven mixer spray head that is winched through the sewer, splitting open two hoses containing a resin and a hardener. This polyurethane formulation is sprayed onto the inside of the pipe, where it dries quickly without clogging the laterals (*Public* 1992). The pipe diameters handled are 10–150 cm (4– 60 in.). Some negotiation of bends is possible, though only in the range of 10–20°. Excellent corrosion resistance characteristics are offered (Stalnaker 1992).

EXCAVATION AND REPLACEMENT TECHNOLOGIES

Excavation and replacement still constitutes the most widely used method of solving sewer problems. Primarily, it involves two scenarios: excavation of the old pipe and its replacement by a new one in the same place or the abandonment of the affected pipe and placement of a new one in a physically or functionally parallel location. Replacement is resorted to when pipes become severely damaged and/or additional capacity is desired, or where other methods cost more or reduce the capacity significantly. At places too, where significant misalignment has occurred, replacement offers the only practical solution. Pipeline replacement materials include traditional items such as reinforced concrete, clay, ductile iron, and variety of plastics (Environmental 1991).

On the negative side, however, excavation and replacement is usually the most expensive method; causes maximum disruption to sewer and traffic flow; affects landscaping; conflicts with other utilities; and leads to problems associated with trench excavation, dewatering and so forth. Moreover, removal and disposal of old pipes is a problem in itself.

TRENCHLESS TECHNOLOGIES

Though trenchless techniques do not essentially fall into the scope of this paper, it would be worthwhile to give a brief resume of its methods and capabilities. A good treatment of trenchless technology is given in the book *Microtunnelling* by Stein et al. (1989). Trenchless technology is a relatively new phenomenon. A sense of confusion, therefore, exists regarding the classification of its various methods and practices. Recourse is, therefore, taken to the standards delineated by ASCE (Committee 1991).

Trenchless excavation construction techniques refer to those methods that involve installation of utility systems below grade without direct installation into an open-cut trench. These methods can primarily be divided into three major categories: horizontal earth boring, pipe jacking, and utility tunneling.

Horizontal Earth Boring

Horizontal earth boring includes methods in which the borehole excavation is accomplished by mechanical means without the workers getting inside the borehole. It can be subclassified into a number of divisions:

- Slurry method
- Compaction method

- Water jetting
- Pipe ramming
- Directional drilling
- Flowmole guide drill
- Auger method
- Microtunneling

The compaction method can utilize either the push rod, rotary, or percussion mechanisms. The auger method can also be performed in two manners using either the track or the cradle. All these methods are primarily governed by a combination of one or more of three basic means: compaction, excavation, and wet boring ("Trenchless technology: alternatives to open-cutting installation" 1992). The compaction process involves the creation of a borehole by squeezing out the soil, thus forming a hole under the ground. On the other hand, excavation methods do this by excavating and removing the spoil out of the hole. Lastly, wet boring utilizes fluid pressure to either loosen and compact the soil by a downhole tool or to transport out the soil from the hole. An interesting variation on the theme is pipe insertion machine (Maloney 1989), which is capable of replacing an existing pipe with a new high-density polyethylene (HDPE) pipe of larger diameter, after destroying the existing pipe using an impact mole.

Pipe Jacking

Pipe jacking requires the workers to work inside the pipe. The pipes are jacked into position from a jacking pit, using the thrust power of hydraulic jacks (rams) to force the pipe forward. To reduce the jacking force, recourse is often made to the use of bentonite slurry on the outside skin of pipe, continuous 24-hr operations and the setting up of intermediate jacking stations. The excavation can be either manual or mechanical, and takes place inside an articulated shield provided for the purpose of keeping the bore open and to ensure worker safety. This method has primarily been applied to reinforced pipes, though it is appropriate for steel, fiberglass, ductile iron, and corrugated pipes as well. The minimum practical diameter is 90 cm (3 ft).

Utility Tunneling

Utility tunneling is used to provide conduits for utilities. Prefabricated steel or precast tunnel liner plates or rib-and-lagging form the lining of the tunnels. The process consists of excavation taking place at the face. The excavation may either be manual or mechanical and takes place inside a tunneling shield. The shield is hydraulically jacked forward during excavation, thrusting against the previously installed liner plates. The jacks are then retracted, lining plates are installed in the tail section of the shield, and the ramming operation restarted. The minimum practical diameter for utility tunneling is 120 cm (4 ft).

EXTENSIONS AND CONCLUSIONS

The previous sections presented a summary of the newest construction technologies for sewer-system rehabilitation. Designers and constructors can benefit from this summary because it consolidates information from a wide range of sources, thus providing a better understanding of these technologies. However, the real value of this understanding is how this knowledge can be extended to a much broader effort to provide the best solutions to infrastructure rehabilitation problems. This section presents two examples of these extensions. The first example describes the specific use of knowledge of construction technologies for the optimal planning of sewer rehabilitation. The second describes how knowledge of construction technologies is crucial within a more global and generic conceptual framework for infrastructure rehabilitation.

Optimal Planning of Sewer Rehabilitation

The problem of sewer systems rehabilitation has been studied from very specific perspectives, including: reduction of infiltration/inflow, increase of in-line storage, increase of basin storage, decrease of the volumes by decreasing the runoff coefficient, or augmenting the paths, among others. Another solution is real-time control, which needs to analyze a sewer network as a whole system, at least for the hydraulics aspect. In addition, from a construction technologies perspective, methodologies that help select from the pool of technologies also give partial, one-sided options to the problem. Finally, we have the approaches that attempt to solve sewer-system problems from a holistic point of view.

A recently completed research project that belongs in this last category is MARESS (Multi-Attribute REhabilitation of Sewer Systems). MARESS provides a new approach for optimal planning of rehabilitation of sewer systems, as an alternative to the crisis-based rehabilitation programs (Reyna 1993). It incorporates (among other aspects) the assessing of the infrastructure condition, construction aspects, and the actual design of the rehabilitation plan in one single model. Although a detailed discussion of MARESS is beyond the scope of this paper, it is relevant to explain some of its principal characteristics because they define the important role that construction technologies play in developing the best solution to sewer-rehabilitation projects. Further details can be obtained in Reyna and Vanegas (1993).

Sewer renovation is not a new area of public-health engineering. Preventive maintenance and renovation in one form or another have taken place from the earliest days of sewer construction, but records of older renovation experience were not kept and are thus not available for reference. During the past few years there has been an increasing interest in maintenance management for urban water-supply and wastewater systems, including preventive and corrective maintenance. The importance of preventive maintenance is evident, and preventive plans often exist but they are not followed due to lack of personnel and funds. Weissert (1989) stresses the need to practice preventive maintenance and not just preach it. Preventive maintenance is the sensible way to avoid larger-scale problems that might occur if the system is left unattended. Preventive maintenance and corrective maintenance complement each other. According to Grigg (1989), "Corrective maintenance includes the three R's: repair, rehabilitation and replacement." Keeping in mind the need of preventive maintenance, it is also necessary to have a methodology for the optimal planning of the rehabilitation of a sewer system with an explicit consideration, leading to the selection of new rehabilitation technologies.

Using MARESS, the crisis-based approach for providing solutions to sewer rehabilitation problems presented in Fig. 1, is replaced by an optimal planning-based approach, as synthesized in Fig. 2. This approach introduces three distinctively different characteristics: (1) Instead of being a reactive response to a given crisis, rehabilitation projects are the result of proactive

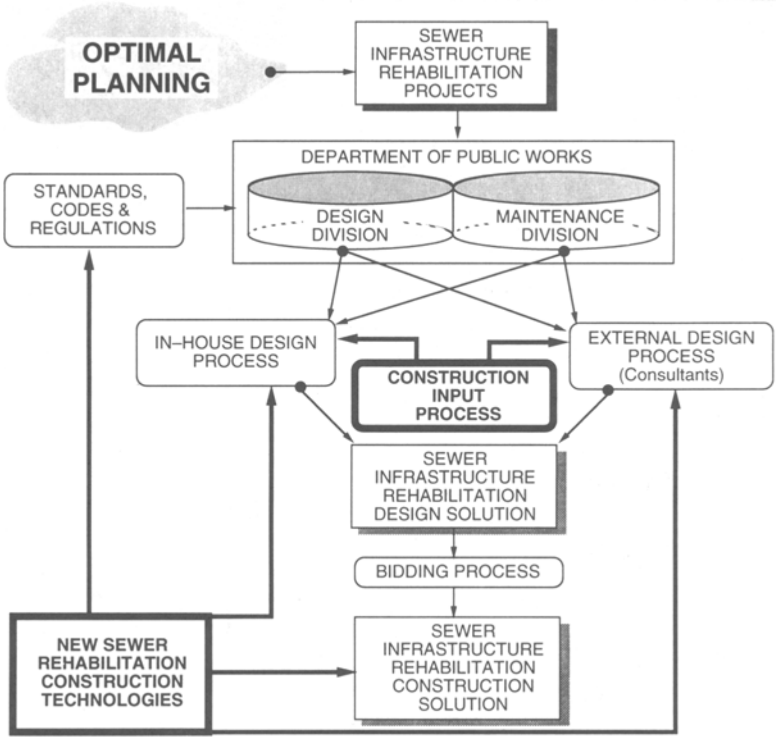

FIG. 2. Optimal Planning-Based Sewer Rehabilitation Approach

optimal planning, where the emphasis is on selective preventive maintenance of sewer system components; (2) instead of separating design from construction, the design solution in this approach actively incorporates construction input as part of the design solution, prior to being issued for bids; and (3) construction technologies for sewer rehabilitation are actively considered at all stages of the process, thus promoting an ongoing process of innovation and improvement.

Integrated Design/Construction Approach for Infrastructure Rehabilitation

As shown in Fig. 3, a more global and generic conceptual framework for infrastructure rehabilitation has two closely interrelated and complementary thrusts. The first thrust focuses on the analysis, assessment, and planning of infrastructure-rehabilitation projects. The second thrust focuses on the implementation and execution of infrastructure-rehabilitation projects.

The primary objective of this approach is the development of new, innovative, and integrated design and construction solutions for infrastructure-rehabilitation problems. This model could be used at any of the different phases of the life cycle of an infrastructure rehabilitation project (e.g., scope definition, conceptual and schematic design, design development, construction planning, or construction execution), and for any of the areas of rehabilitation (e.g., electric power, gas and liquid fuels, telecommunications, transportation, and water and sewer systems).

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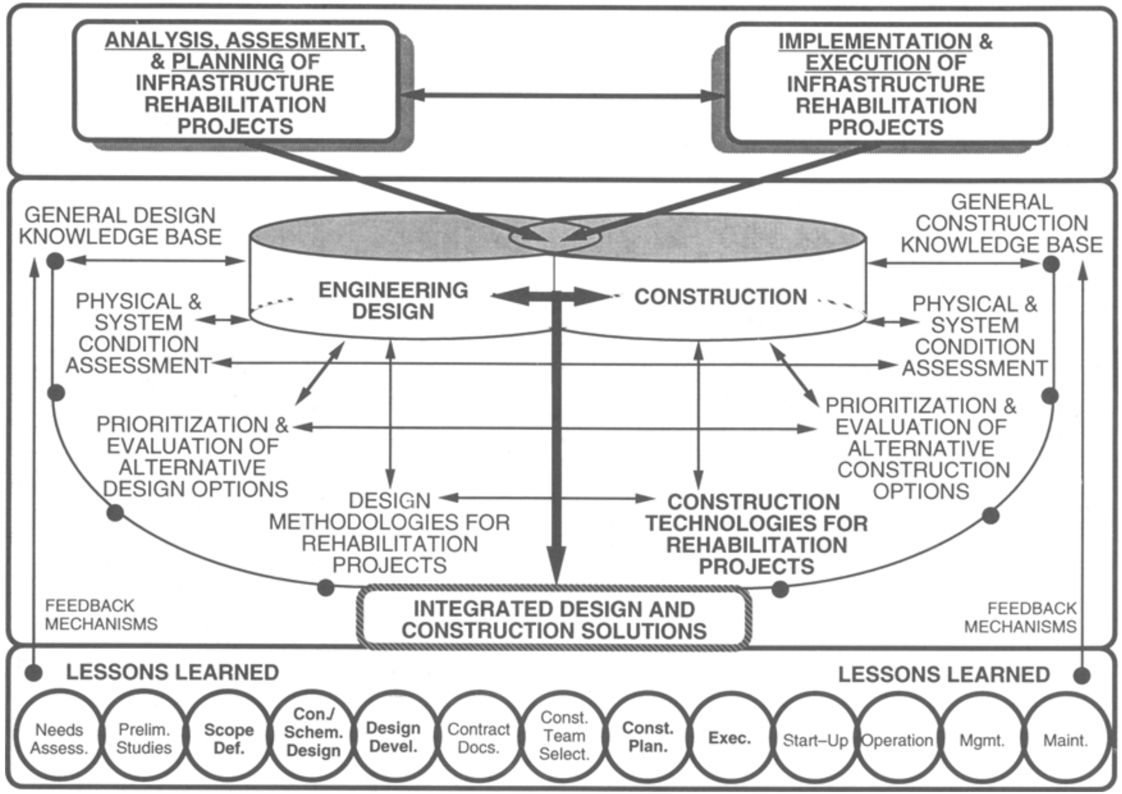

FIG. 3. Conceptual Framework for Integrated Design/Construction Approach for Infrastructure Rehabilitation

Within this framework, a solution to an infrastructure rehabilitation problem would require close integration of the engineering and construction processes for five primary tasks:

1. The definition of state-of-the-art infrastructure rehabilitation design and construction knowledge bases.
2. The assessment of the physical and system condition of the problem to define the parameters that will guide engineering design and construction planning.
3. The development of new (or application of existing) methods to prioritize and evaluate alternative design and construction options.
4. The development of new (or application of existing) specific design methodologies and construction technologies for infrastructure rehabilitation.
5. The development of dynamic feedback mechanisms that capture design and construction lessons learned at any phase of the life cycle of an infrastructure rehabilitation project, and their incorporation into the design and construction knowledge bases.

From the figure, it is important to realize the fundamental role played by construction technologies.

CONCLUSIONS

Rehabilitation projects contain unique characteristics that differentiate them from other construction projects. Specifically for sewer rehabilitation, there is a wide range of technologies currently available, that, due to existing institutional barriers and the risk-adverse and conservative mentality of designers, many times are not fully exploited. Thus, a starting point for the development of more optimal solutions to these types of problems is the establishment of the state of the art of these technologies. This paper achieves this. More importantly, though, the real value of an understanding of these technologies lies in how their knowledge can be integrated at a micro level (e.g., the specific context of sewer rehabilitation), and at a macro level (e.g., the global context of infrastructure rehabilitation). This paper provides an example of these extensions.

More work needs to be done in this area. The imperative need to develop and implement efficient design and construction solutions for infrastructure problems, within ever decreasing resources and tighter constraints, provides a strong incentive for further studies. As mentioned previously, an understanding of these technologies is just the first step.

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APPENDIX. REFERENCES

Ainsworth, L. D., Phelps, S., and Cantrell, D. (1989). "Slip-lining avoids replacement of break-plagued sewer force main." *Public Works*, Aug. 73–74.

America's infrastructure: a plan to rebuild. (1983). Associated General Contractors, Washington, D.C.
Bible, D. W. (1992). "Trenchless sewer reconstruction in Nashville." *Water Envir. and Tech.*, May, 44–46.
Civil Engineering Research Foundation. (1991). "Setting a national research agenda for the civil engineering profession." *Final Rep.*, Civil Engineering Research Foundation, Washington, D.C., 1, Aug.
Civil Infrastructure Systems Task Group. (1993). "Civil infrastructure systems research: strategic issues." (1993). *Report*, Civ. Infrastructure Systems Task Group, Nat. Sci. Foundation, Washington, D.C.
Committee on Construction Equipment and Techniques. (1991). "Trenchless excavation construction methods: classification and evaluation." *J. Constr. Engrg. and Mgmt.*, ASCE, 117(3), 521–536.
Cooper, S. E., and Heitzman, G. C. (1992). "Water main rehabilitation using silicote lining." *Proc. Water Resour. Sessions at Water Forum '92*, ASCE, Baltimore, Md., Aug.
Day, M. D. (1990). "Balancing needs: Growth & infrastructure rehabilitation." *Proc. Water Resour. Infrastructure: Needs, Economics and Financing*. Water Resources Planning and Management Division, ASCE, Ft. Worth, Texas, Apr.
Delleur, J. W. (1989). "Urban stormwater infrastructure: rehabilitation activities in the United States." *Proc. Engrg. Foundation Conf., Urban Water Res. Council*, ASCE, New York, N.Y. Oct.
Department of Housing and Urban Development, Office of Policy Development and Research, Building Technology Division. (1984). *Utility Infrastructure Rehabilitation Report*. Brown and Caldwell, Walnut Creek, Calif.
Environmental Protection Agency, Office of Research and Development. (1991). "Sewer system infrastructure analysis and rehabilitation." *Rep. No. EPA/625/6-91/030*, Cincinnati, Ohio.
Fedotoff, R. C., Bellows, P. H., Frutchey, R. W., and Thomson, J. (1991). "Trenchless tecniques improve pipelines." *Water Environment and Tech.*, Apr.
Fiddes, D. (1989). "UK urban stormwater control—institutional issues." *Proc. Engrg. Foundation Conf.*, Urban Water Research Council, ASCE, Davos Platz, Switzerland, Oct.
Frank, J. E., and Falconer, M. K. (1990). "The measurement of infrastructure capacity: Theory, Data Structures, and Analytics." *Comput. Environ. Urban Syst.*, 14, 283–297.
Giglio, J. M., Goldmark Jr., P. C., Jackson, L., Holmer, F., and Wallison, F. K. (1988). "Fragile foundations: A report on America's public works." *Final Rep. to the President and Congress*, National Council on Public Works Improvements, Washington, D.C.
Goodenough, K., and Smith, D. (1991). "Lining up in Santa Barbara." *Public Works*, Apr., 74–75.
Grigg, N. S. (1985). *Infrastructure engineering and management*. John Wiley and Sons, Inc., New York, N.Y.
Inspector handbook for sewer collection system rehabilitation. (1991). Nat. Association of Sewer Service Companies, Altamonte, Fla.
Jones, M. P. (1992). "A review of current U.K. techniques for rehabilitating water mains." *Proc. Water Resour. Session at Water Forum '92*, ASCE, New York, N.Y., Aug.
Karaa, F. A. (1989). "Infrastructure maintenance management system development." *J. Profl. Issues Engrg.*, 115(4).
Maloney, S. W. (1989). "In-place replacement of underground pipes." *Proc. First Int. Conf. on Underground Infrastructure Res.*, AWWA Research Foundation, Washington, D.C., Nov.
McAlpine, G. (1991). "The Danby Pipe Renovation System." *Proc. 18th Annual Conf. and Symp.*, Water Resources Planning and Management Division, ASCE, New Orleans, La., May.
McCullouch, B. G. (1991). "Repair/rehabilitation of deteriorated drainage pipes."

Rep. No. FHWA/IN/JHRP-91/14, Joint Highway Research Project, School of Civ. Engrg., Purdue Univ., West Lafayette, Ind.
Murzyn, R. K. (1990). "City tackles major sanitary sewer system rehabilitation with new process." *Public Works*, Aug.
National Science Foundation. (1993). "Civil infrastructure systems research: Strategic issues." *Rep.*, Civ. Infrastructure Systems Task Group, Washington, D.C.
"No-dig pipe restoration: U-liner applications." (1989). *Florida Water Resour. J.*, Aug., 4.
Osborn, L. E. (1990). "The new generation of rehabilitation." *Proc. 17th Water Resour. Plng. and Mgmt. Div. Conf.*, ASCE, Fort Worth, Tex., Apr.
Pena, R., and Holstad, M. S. (1989). "Albuquerque's sewer rehabilitation program." *Public Works Magazine*, Dec., 61–63.
Public works manual. (1992). Apr.
Quimpo, Rafael G., and Shamsi, Uzair M. (1991). "Reliability-based distribution system maintenance." *J. Water Res. Plng. and Mgmt.*, ASCE, 117(3), 321–339.
Reyna, S. M. (1993). "Optimal planning of sewer systems rehabilitation," PhD thesis, Purdue University, West Lafayette, Ind.
Reyna, S. M., and Vanegas, J. A. (1993). "Optimal planning of combined sewer rehabilitation." *20th Anniversary Water Resour. Plng. and Mgmt. Div. Conf.*, ASCE, Seattle, Wash., May 3–6.
Robison, J. (1989). "National perspective on infrastructure costs." *Proc. First Int. Conf. on Underground Infrastructure Res.*, American Water Works Association Research Foundation, Washington, D.C., Nov.
Specification guidelines for sewer collection system maintenance and rehabilitation. (1992). Nat. Association of Sewer Service Companies. Altamonte, Fla.
Stalnaker, R. (1992). "An end to trench warfare." *Water Environment and Tech.*, May, 47–53.
Stein, D., Mollers, K., and Bielecki, R. (1989). *Microtunneling*. Ernst and Sohn, Berlin, Germany.
Thomson, J. C. (1991). "Pipeline rehabilitation: Underground options." *Civ. Engrg.*, ASCE, May, 64–66.
"Trenchless technology: Alternatives to open-cutting installation." (1992). *Public Works*, April, 73–75.
U-Liner, the better way . . . . (1991). Midwest Pipeliners, Columbus, Ohio.
Water Research Centre. (1983). *Sewerage rehabilitation manual.* Water Res. Ctr., Swindon, Wiltshire, England.
Weil, G. J. (1990). "Remote infrared thermal sensing of sewer voids." *Proc. 17th Annual Conf.*, Water Resources Planning and Management Division, ASCE, Houston, Tex., Apr.
Weissert, T. (1989). "Don't just preach preventive maintenance, practice it." *Water Engrg. and Mgmt.*, 136(1), 32–35.
Zurawski, J. F. (1992). "Repair and rehabilitation of brick sewers with shotcrete." *Public Works*, June, 47–47.