Chapter 1

Pipeline Renewal Methods

Pipeline renewal is typically accomplished by one of two approaches: rehabilitation or open-trench construction, although other trenchless methods are also used. Trenchless technology is a type of subsurface construction work that requires little or no surface excavation and no continuous trenches. This chapter provides guidance in selecting between rehabilitation and open-trench construction and in determining which rehabilitation method is most appropriate for meeting goals.

The renewal of water mains is performed for three primary reasons:

1. Water Quality Improvement: to improve the quality of the water received by the consumer
2. Hydraulic Improvement: to increase the hydraulic capacity of the pipeline
3. Structural Improvement: to reduce leakage, decrease repair frequencies, lessen risk of property damage, and improve reliability.

Compared with conventional open-trench replacement, pipeline rehabilitation methods are often less expensive and less disruptive to the community; however, rehabilitation is not appropriate for all situations.

As described in other chapters in this manual, many different water main rehabilitation techniques exist, offering a variety of benefits. The best choice of method for each situation will depend on several factors, including: (1) the reason for the rehabilitation, (2) comparative costs, (3) site conditions, and (4) expected life-cycle performance.

This chapter provides guidance in selecting a pipeline renewal method, including a series of decision trees that can be used to help determine which types of methods should be considered.

DISTRIBUTION SYSTEM WATER QUALITY IMPROVEMENT

Water main rehabilitation is frequently performed to mitigate water quality deterioration that occurs within the distribution system. The goal is to improve water quality at the point of use. The improvements can be very dramatic, particularly when the existing main is unlined cast iron.

In most cases, the water quality benefits achieved by the various pipeline rehabilitation methods are fairly equal. This assumes that the materials being employed are certified in accordance with NSF/ANSI Standard 61, and industry accepted standards are employed. It also assumes that the water is not particularly soft. When the water is soft, problems with high pH can occur if cement–mortar lining is used.

The quality of treated drinking water can vary considerably, both from system to system and within a system, as a result of deterioration after it leaves the treatment plant and comes in contact with the interior of distribution system piping. Over time, changes in water chemistry can cause problems throughout the distribution system, ultimately affecting the quality of the water delivered to the end user. The deterioration of water quality that occurs within the water distribution system is often signaled by customer complaints regarding the clarity, color, taste, and odor of the water. Although the water may be safe to drink, it may be aesthetically unpleasant due to sediment that has been stirred up or by biological processes that can thrive in highly scaled pipelines and impart an odor to the water. However, the concern is not always simply about aesthetics. Water stagnation and chlorine depletion occur in highly scaled pipelines, resulting in greater risk of coliform regrowth. The majority of these problems fall into three categories: sedimentation, scaling, and biofilm formation.

Sedimentation

Sedimentation is the process whereby solids settle out of water moving at low velocity in a main, reducing interior cross section and capacity and becoming a potential source of customer complaints about water quality. Source water pipelines or pipelines carrying unfiltered or improperly treated water can be subject to deposits of sand, silt, or organic materials. In pipelines receiving well water, particulates from oxidation of iron or manganese are also common, if the water is not filtered. In extreme cases, sedimentation can also contribute to hydraulic problems, particularly at low points in the pipe. The most common source of sediment is the internal corrosion of the pipeline itself.

In smooth-walled pipelines, sediment generally moves through the system at moderate flow velocities and does not accumulate. However, where the pipeline is heavily scaled, sediment settles into the recesses of the scale and builds up over time. This sediment can then be stirred up when the flow velocity increases (e.g., a fire hydrant is opened) or the direction of flow reverses. The result can be severely discolored water as a large volume of sediment becomes suspended and is delivered to the customer's tap.

Scaling or Tuberculation

Scaling is the formation of hard deposits on the inside wall of the pipe. These deposits are frequently the by-product of pipe corrosion, wherein iron combines with calcium and other minerals within the water to form *tubercles*. The process, often called *tuberculation*, is assisted by bacteria within the scale that feed on iron leached from the pipe. Although scaling is most pronounced in cast-iron pipes, it is also commonly found in unlined steel pipes, copper pipes, concrete, and asbestos–cement pipes. Figure 1-1 shows a fairly typical tuberculated cast-iron pipeline.

Figure 1-1 Pipe with tuberculation caused by corrosion

Before the 1960s, many iron pipes were installed without effective, long-lasting linings to protect the interior surfaces. These pipes often experience internal corrosion and develop tubercular scales. This scaling restricts the flow and creates areas where sediment is deposited, and chlorine depletion occurs.

Water discoloration complaints can occur when these sediment deposits are stirred up as previously described; however, discoloration can also occur if the corrosion activity within the pipeline is particularly high. If the scales are removed and a lining is not subsequently installed, exposure of the underlying iron or steel pipeline often results in increased corrosion activity and more frequent complaints about water discoloration. Such corrosion activity can be controlled to some extent through water chemistry (corrosion inhibitors), but cleaning of pipelines without lining is generally not recommended.

Biofilm Formation

Biofilms can develop within pipe made from any type of material; however, biofilms are most common within highly scaled cast-iron pipe, where sediments and recesses allow iron-reducing bacteria to thrive in the absence of effective disinfectant. As the pipelines corrode and tubercles develop, the hospitality of the environment for biofilm increases. The greater the roughness of the pipe surface, the harder it is for an effective disinfectant residual to be maintained near the pipe surface. The reduction of the iron leached from the pipe also provides the energy source for the bacteria.

Biofilms also form readily in raw water systems or portions of the finished water system where water is high in iron or manganese or other nutrients. Such biofilms take the form of slimes, i.e., soft and filamentous. Even where scales do not form, these biofilms can severely affect water clarity and produce taste-and-odor problems. They can also significantly diminish hydraulic capacity.

HYDRAULIC IMPROVEMENT

Increasing roughness and the buildup of scale or slime inside water distribution piping can greatly reduce the hydraulic performance of the system. This can significantly impact the ability to deliver adequate fire flows and can also affect pressures and flows available to customers.

Hydraulic engineers are able to calculate head losses and flow in pipes using the empirically derived Hazen–Williams formula, which relates flow to the physical properties of the pipe and pressure changes due to friction; however, the Hazen–Williams equation cannot be applied to all fluids in all conditions. It is only valid for ambient temperatures (40°F to 75°F [4.4°C to 23.8°C]) and at turbulent flow (Reynolds numbers above 10^5). For liquids outside these parameters, the Darcy–Weisbach formula is more reliable for frictional head loss calculations at steady-state flow. In more complicated instances, computer models based on Hardy Cross are more accurate. For the discussion in this manual, the Hazen–Williams equation is:

$$V = kCR^{0.63}\,S^{0.54} \qquad \text{(Eq. 1-1)}$$

where:

V = velocity, ft/sec (m/sec)
k = conversion factor
R = hydraulic radius, ft (m), which is the cross-sectional area of the pipe divided by the wetted perimeter
C = Hazen–Williams roughness coefficient
S = slope of the hydraulic grade line, ft/ft (m/m)

C is a measure of the roughness of the interior of the pipe. Expressed in terms of *C*, the formula can be stated several ways. Once such way is stated as:

$$C = 2{,}466QD^{-2.63}\,H^{0.54}\,L^{0.54} \qquad \text{(Eq. 1-2)}$$

where:

C = Hazen–Williams roughness coefficient
Q = quantity of flow in a pressure conduit, mgd (m^3/d)
D = nominal diameter of the pipe, in. (mm)
H = head loss, ft (m) of water
L = length of pipe, ft (m)

The Hazen–Williams *C* factor, and hence the flow in a pipeline, depends on the type of pipe and its interior condition (see Table 1-1). For a given velocity, increased internal surface roughness (changing laminar to turbulent flow) leads to greater pressure loss. By measuring pipe flows and pressure changes between two points along a pipeline, operators can calculate Hazen–Williams *C* factors and determine the degree the pipeline has become roughened and constricted. These data help in making informed decisions about which process to employ to restore hydraulic efficiency. Collecting data for the Hazen–Williams *C* factor after employing a cleaning or pipe rehabilitation process is also a useful way to gauge the impact of the system improvements.

Table 1-1 Hazen–Williams roughness coefficient

Condition	*C*
New pipe	130–140
Fair to normal (interior clean)	100
Significant reduction in pipe capacity	70
Severe problem—interior cross section greatly reduced	30–50

Pipeline rehabilitation very frequently results in significant improvement of system hydraulics, particularly where a cast-iron main is choked with tuberculation. Not only is a smoother pipe surface achieved, but at times, the effective flow cross section can be increased significantly.

Because the various methods use different materials and result in different internal diameters, the various methods achieve different degrees of hydraulic improvement. Table 1-2 provides a general comparison of the hydraulic improvements that the various rehabilitation methods can provide.

Moderate hydraulic improvement can also be achieved by some of the pipeline cleaning methods.

STRUCTURAL IMPROVEMENT

The structural performance of water mains deteriorates over time due to several causes. Cast-iron, ductile-iron, and steel piping are subject to internal and external corrosion, resulting in pitting and wall thinning, which can lead to leaks and eventual burst failures. Cement-based pipes such as asbestos–cement and concrete pipe may also be subject to deterioration due to corrosion of the cement matrix and/or steel reinforcement. In addition, all types of pipe, including plastic, may be subject to joint failure between pipe lengths and hence excessive leakage, which can in turn lead to washout of bedding and subsequent structural failure.

Such structural and leakage failures can have direct consequences such as high repair costs, water quality problems, service interruptions, and loss of treated water. They may also have indirect consequences in terms of the economic damage associated with pipe bursts and the public relations damage to the service provider.

The structural improvements afforded by the techniques discussed in this manual vary considerably. Cement–mortar lining and epoxy lining are generally considered *nonstructural* because they offer very minor structural improvements at best. Other methods arguably offer the same structural integrity achieved by a new pipeline installed using conventional open-trench construction. In selecting a pipeline rehabilitation method, one of the key considerations is matching the method to the pipeline. A nonstructural method (i.e., Class I*) is absolutely appropriate for a pipeline that has experienced very little deterioration, but this method would not be appropriate where external corrosion has caused significant weakening of the pipe and where this corrosion is expected to continue.

Table 1-2 General comparison of hydraulic improvements

Hydraulic Improvement Anticipated	Rehabilitation Method
Modest hydraulic improvement	Loose sliplining
Moderate hydraulic improvement	Cement–mortar lining Epoxy and other polymer lining Modified sliplining (close-fit) Cured-in-place lining
Greater hydraulic improvement	Pipe bursting
Unlimited hydraulic improvement	Open-trench construction

* See appendix A for definition of Class I, II, III, and IV linings.

WATER MAIN CONDITION EVALUATION

Before employing a nonstructural or semistructural method, an evaluation of the structural condition of the water main is warranted. This evaluation can range from simple and inexpensive, to high-tech and quite costly. The more valuable the pipeline, the more time and money the utility should invest in making the right decision.

The following methods have been used successfully to guide decisions regarding pipeline renewal:

- **Leak/break performance.** Where repair records indicate that a pipeline has had few or no corrosion-caused failures and the pipeline has been in service for many decades, it is often assumed that external corrosion activity is minimal, and the pipeline is a good candidate for a nonstructural lining.
- **Sample extraction/evaluation.** In the United Kingdom, pipeline samples are exhumed then grit blasted to remove graphitization and expose the corrosion pits. The remaining life of the pipeline is then estimated using a method that examines pit depth and pit spacing. One U.K. utility replaces the pipe, for instance, if the estimated remaining life is less than 20 years, and uses a nonstructural lining where the life expectancy is 30 years and more. Semistructural linings are used for those in the middle, with life expectancies between 20 and 30 years.
- **In-situ testing.** For pipelines where a greater investment is warranted, nondestructive evaluation methods should be considered. Depending on the type of pipe, remote field technology or remote field eddy current can be used to find areas of weaknesses throughout the pipeline. Other techniques have been used for spot evaluations at locations of particular concern. Acoustic detection methods of various types are used to search for leaks or detect the sounds of incipient failure.

PRIORITIZATION

Because budgets are always limited, a method of prioritizing work is important. If a primary driver for the renewal program is structural improvement, the pipelines that pose the highest risk should receive the highest priority. In assessing risk, it is helpful to recognize that risk has two components: probability and consequence. For something to be risky, it must be both likely to occur and have significant consequences. This concept is often expressed mathematically:

$$\text{Risk} = \text{Probability} \times \text{Consequence} \qquad \text{(Eq. 1-3)}$$

To perform this mathematical calculation requires more data (and better data) than are typically available. So instead, it is often helpful to look at *relative* risk as expressed in Table 1-3.

Prioritization can also be performed using regression analysis. With sufficient data regarding the age, soil conditions, pressure, pipe characteristics, etc., effective statistical models have been developed for specific systems. However, regression models built for one system have not been demonstrated to work on other systems.

Table 1-3 Relative risk assessment

Probability		Consequence: Low	Consequence: Medium	Consequence: High
	High	Repair on failure	Schedule renewal	Fix now
	Medium	Repair on failure	Assess proactively	Schedule renewal
	Low	Repair on failure	Monitor	Assess proactively

COSTS AND BENEFITS

Many factors influence the cost of a water main renewal project. Some of the factors are: project size, pipeline size, method used, bypass system requirements, traffic conditions, number of laterals, number of valves or fittings, paving requirements, etc. Costs are also influenced by the availability of local contractors who have the equipment and knowledge needed to perform the rehabilitation. Generally, the less-structural spray-applied methods (Class I) will be less expensive than more fully structural (Class IV) methods.

The cost of a rehabilitated pipeline typically ranges from 25 percent to 100 percent of the cost of conventional open-trench construction. However, even where there are no significant cost savings, rehabilitation may still be preferred because it results in fewer construction impacts to the community.

When properly applied to an appropriate pipe, the life expectancy goal of a rehabilitated pipeline should be similar to that of a new pipeline—50 to 100 years.

REHABILITATION SOLUTIONS

This manual describes several possible solutions to problems arising from corrosion and deposition of internal scales. These range from simple periodic cleaning to replacement of the pipe using trenchless techniques. All of the solutions discussed in the manual make some use of the existing pipe, either as part of the rehabilitated system (renovation solutions) or as a convenient route for installation of new piping (replacement solutions). Solutions involving installation of a replacement pipe along a new route, such as open-trench laying, directional drilling, and microtunneling, are outside the scope of this manual.

Selecting the optimal solution to a specific pipeline problem is a complex process involving both technical and economic considerations. Both the Water Research Foundation and several AWWA Technical and Educational Council (TEC) committees are developing computer-based decision tools to assist utility engineers in this process. This work is expected to come to fruition while this edition of the manual remains in effect. In the meantime, the following guidelines may prove useful.

SELECTION OF REHABILITATION SOLUTIONS

Key elements in the selection of a rehabilitation solution are:

1. The exact nature of the problem(s) to be solved
2. The hydraulic and operating pressure requirements for the rehabilitated main
3. The materials, dimensions, and geometry of the water main
4. The types and locations of valves, fittings, and service connections
5. The length of time in which the main can be taken out of service
6. Site-specific factors

The aim of the selection process is to consider all these factors and to arrive at the most cost-effective, technically viable solution. Ideally, the cost estimate should include not only direct contracting and related costs but also indirect costs associated with public disruption and longer-term maintenance and other life-cycle costs.

One approach to rehabilitation method selection is summarized in Figures 1-2, 1-3, and 1-4. Together, these charts provide a framework for selecting or rejecting groups of rehabilitation methods, depending on the nature of the performance problems, hydraulic requirements, and some site-specific factors. In some cases, the charts indicate use of lining techniques classified as either Class I (nonstructural), Class II/III (semistructural), or Class IV (structural). A more detailed discussion of this classification system and of other key design issues associated with such lining techniques is presented in appendix A.

The figures do not list cleaning as a solution for water quality or flow and pressure problems. Cleaning with one of the various techniques discussed in the manual may well offer the lowest-cost immediate solution to many of these problems. It may offer a long-term solution if repeated as required or combined with chemical treatment of water to prevent or delay recurrence of the original problem. However, cleaning is more frequently used as a necessary preliminary step before carrying out one of the lining processes described in the manual.

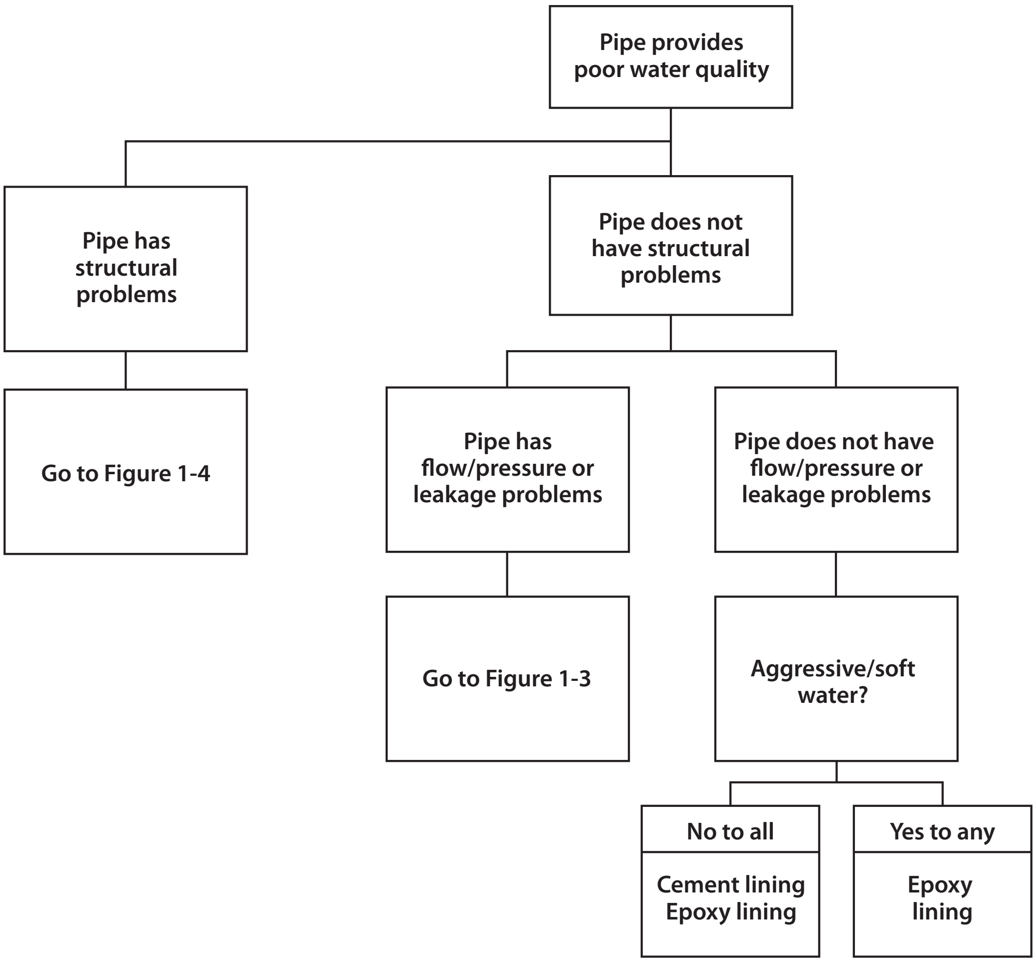
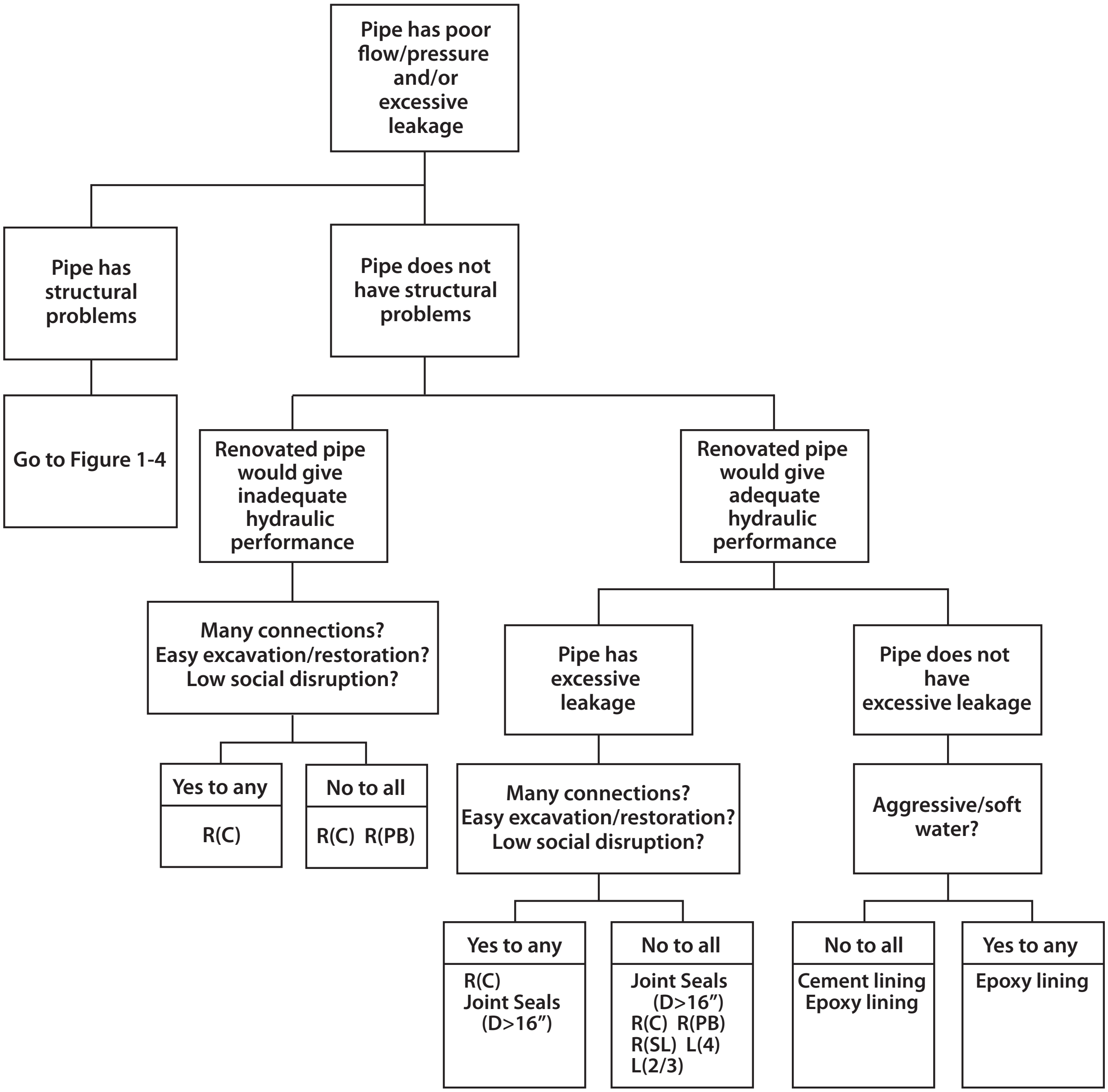
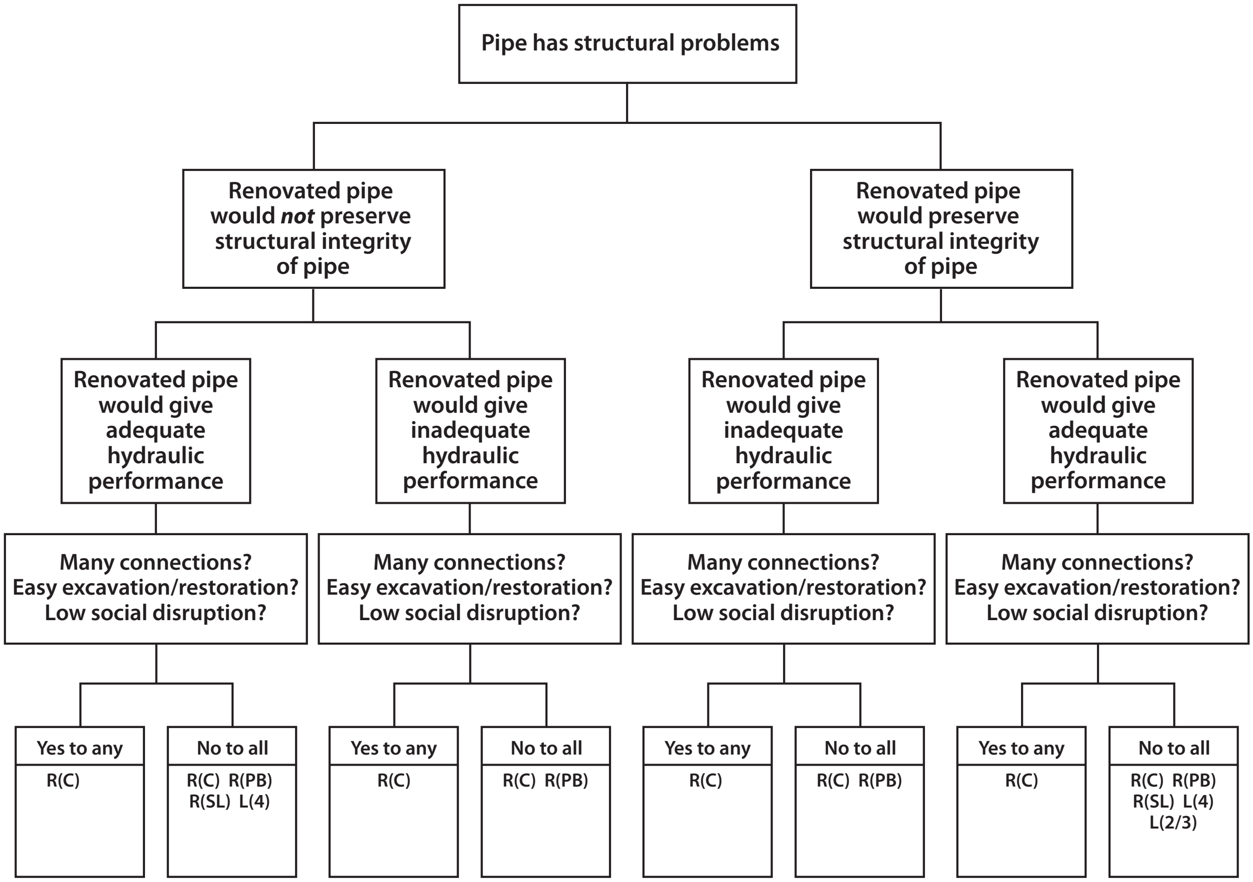


Figure 1-2 Selection of rehabilitation techniques to resolve water quality problems



Notes:
R(C)—Replacement (conventional or boring/directional drilling)
R(PB)—Replacement (pipe bursting)
R(SL)—Replacement (sliplining)
L(2/3)—Lining (semistructural—Class II/III)
L(4)—Lining (structural—Class IV)

Figure 1-3 Selection of rehabilitation techniques to resolve flow, pressure, and leakage problems



Notes:

- R(C)—Replacement (conventional or boring/directional drilling)
- R(PB)—Replacement (pipe bursting)
- R(SL)—Replacement (sliplining)
- L(2/3)—Lining (semistructural—Class II/III)
- L(4)—Lining (structural—Class IV)

Figure 1-4 Selection of rehabilitation techniques to resolve structural problems

REFERENCE

American National Standards Institute (ANSI). 2012. Drinking Water System Components—Health Effects. NSF/ANSI 61-2012. 198. Ann Arbor, Mich.: NSF International.