Catastrophic failures of large-diameter pipelines cost municipalities far more than the preventive measures that could mitigate such failures. Traditionally, utilities procure inspection and engineering services one project at a time. With this approach, a utility is unable to take advantage of economies of scale. This limitation can be overcome by adopting a long-term, ongoing, programmatic approach to pipeline condition assessment and rehabilitation.
PROVIDENCE WATER

Providence Water in Providence, R.I., is the main supplier of potable water for approximately 600,000 people in the state of Rhode Island. The Providence Water pipeline inventories include large-diameter, prestressed concrete cylinder pipe (PCCP) built in the 1950s and 1960s. Finished water is transmitted from Providence Water’s 144-mgd Philip J. Holton Water Purification Plant to the distribution system through two major transmission mains: the 4.1-mi-long, 90-in.-diameter Scituate Tunnel and Aqueduct and a 9.5-mi-long, 78-in.- and 102-in.-diameter PCCP supplemental tunnel and aqueduct (STA). The STA was constructed in the 1960s to provide a redundant transmission pipeline to the distribution system as well as additional transmission capacity. This redundancy gives Providence Water the ability to shut down one of the lines for inspection and repair purposes without compromising customer service. A schematic of Providence Water’s Transmission Main System is shown in Figure 1.

ASSESSMENT AND REHABILITATION PROGRAM

Providence Water employs a holistic, programmatic approach to pipeline assessment and rehabilitation. From regularly scheduled inspections to the use of novel condition assessment and rehabilitation technologies, Providence Water has been proactive in using innovative tools for managing its pipelines.

Program history. The impetus for the assessment and rehabilitation program was the rupture of a 102-in.-diameter PCCP aqueduct in November 1996. The rupture occurred near the system-end of the line and required emergency response, repair, and failure investigation. This event raised concerns about the structural integrity of the entire aqueduct system and its susceptibility to failure. So, a comprehensive investigation program was developed in 1996, including a failure analysis and comprehensive pipeline risk assessment that recommended recurring inspections. These recurring inspections have led to numerous investigations and repairs that have been performed in phases over the past 20 years. Figure 2 shows the program’s timeline since its inception. This program has helped Providence

FIGURE 1 Schematic of the Providence Water transmission main system

FIGURE 2 The Providence Water program timeline
Water make informed decisions about the long-term operation and maintenance of its aqueduct system, especially when more urgent attention is required to prevent catastrophic failure.

**Inspections.** Providence Water has used various inspection technologies, such as impact echo, visual inspection, hammer sounding, soil and groundwater testing, electromagnetics, failure risk curves, and long-term fiber-optic monitoring of its large-diameter PCCP asset. Internal inspections are conducted on a five-year interval, and one or more distressed pipes that warrant immediate repair have been identified during each inspection. The fiber-optic monitoring system has also identified accelerating patterns of wire breaks on several pipes that have been excavated, verified, and repaired. Several million dollars have been spent on this asset since the late 1990s in a proactive inspection and repair approach, significantly less than if the pipe had been run to the point of failure and required emergency response, while also deferring the need to budget tens or hundreds of millions to replace the entire line.

With the maturing of the program, a comprehensive inspection and rehabilitation effort for the 78- and 102-in.-diameter aqueducts commenced in 2005. The aqueducts were inspected in four separate phases: two phases for the 102-in.-diameter aqueduct in 2005 and 2006 and two phases for the 78-in.-diameter aqueduct in 2007 and 2008. Additionally, the 78-in.-diameter aqueduct was inspected in 2013 and 2016. The inspections were conducted in phases to maintain uninterrupted service to two wholesale water customers along the pipeline routes. In 2011 and 2016, Providence Water executed contracts to inspect and rehabilitate the 102-in.-diameter aqueduct on its recurring five-year inspection schedule. Each of the inspection phases also included the design and construction of many improvements to the aqueducts, including new access manholes, new control valves, piping and valve improvements to existing blow-off structures, new sluice gates at control structures, and general easement maintenance and landscaping. Each section of the aqueduct system to be inspected was isolated with new 78- and 102-in. control valves that were installed specifically to maintain service to two wholesale customers while any portion of the aqueduct was down for inspection or repair.

Recurring inspections have led to numerous investigations and repairs that have been performed in phases over the past 20 years.
This program has helped Providence Water make informed decisions about the long-term operation and maintenance of its aqueduct system, especially when more urgent attention is required to prevent catastrophic failure.

included complete and thorough visual inspections, structural hammer soundings, and electromagnetic inspections to evaluate the condition of the PCCP prestressing wires and estimate the number and location of broken wires.

With the estimated number of broken wires in pipe sections along the aqueducts from the electromagnetic inspection results, a failure-risk analysis of distressed pipe sections was completed to prioritize additional forensic investigations and repairs. The failure-risk assessments used finite element models of failure of PCCP based on number of broken wires, hydrostatic operating pressures, depth of bury, bedding and installation conditions, serviceability, structural damage, and ultimate strength to determine the risk of failure and the repair priority of suspect pipe sections identified by the inspections.

Rehabilitation. On the basis of the risk, type, severity, and extent of any internal and external deterioration identified, immediate repairs to pipe sections have been performed. The repairs have included repair mortar for debonded concrete coating, external reinforcing, post-tensioning tendon repairs, reinforced concrete encasement for pipes with shallow cover, pipe replacement, new manholes for future access, exterior and interior mortar patching, cleaning of prestressing wires and application of fiber reinforced polymer (CFRP) as a structural lining applied on the inside of a potable water PCCP main. Providence Water was the first to use this application in the 1990s. A photograph demonstrating the application of CFRP on Providence Water's 102-in. PCCP aqueduct is shown on page 49. Since its original carbon fiber pipeline strengthening project, Providence Water has relied on the internal application of carbon fiber repairs, particularly as a solution for remote or difficult access issues in which open-cut techniques are not feasible or are prohibitively expensive. Providence Water has leveraged the knowledge gained from its program to create predictability in its systems and extend the service life of its PCCP.

CFRP DESIGN AND INSTALLATION CONSIDERATIONS

Using CFRP composites for PCCP repair entails a detailed construction specification requiring certified and tested materials, specially trained construction inspectors, and a detailed inspection protocol for quality assurance. AWWA is nearing completion of development of a new standard for strengthening of PCCP by using carbon fiber and should be moving to publication in the near future.

The installation process for CFRP is a “wet lay-up” process in which the dry CFRP fabric is saturated in the field with epoxy resin and is then manually applied internally at the designed number of longitudinal and circumferential layers to the structurally deficient pipe. Before commencing repairs, the host pipe condition is assessed, emergency plans are completed, the air is checked for hazardous gases, and ventilation and dehumidification systems are established to maintain environmental controls. High-pressure water blasting is used to remove concrete from the inner core surface as required to meet the surface profile requirements of the project. Prior to the installation of the CFRP reinforcement, a pull-off test is performed to confirm design assumptions. This procedure is necessary to confirm the existing condition of the internal concrete core and designed bond between concrete core and CFRP material. In preparation for the fiber saturation process, epoxy resins are mixed above ground onsite. A specially designed saturator is used to saturate measured lengths of 2-ft-wide dry fiber fabric. When saturation is complete, the composites are applied within the maximum allowable 3 h.

For all applications, once the surface is properly prepared and the walls have dried, additional repairs, such as spalling and joint or cylinder repair, can be conducted if necessary. Next, the surface is primed for application of composite layers. The saturated rolls of composite are applied to the pipe wall. When the composite is applied in the circumferential direction, the pipe is strengthened for hoop stress. When the composite is applied in the longitudinal direction, some level of resistance to bending moments is provided. A final topcoat further protects the composite layers.

As with most construction projects, some unforeseen events and field complications can arise. Over the years during various CFRP programs at Providence Water, end
joint details for the transition of CFRP back to host pipe have been improved to chip out the end joints and create a watertight barrier between the steel cylinder and the CFRP liner. The chipping process initially proved more difficult than expected and took more time than anticipated. Recent installations have proved successful and have been verified during follow-up inspections. Figure 3 shows a comparison of end joint liner termination details that have been developed to address the concern of providing a watertight seal to the steel cylinder at the pipe joints.

**COST EFFICIENCIES**

A programmatic approach provides opportunities to increase cost efficiency, allowing the utility to take advantage of economies of scale and providing opportunities to develop and train in-house resources for inspection of rehabilitation projects. Several factors contribute to improved cost efficiency. Because of their larger size and ongoing nature, programs typically attract more qualified contractors, increase the bid competition, and result in better pricing. Additionally, cost savings can be realized during the design phase by standardizing contract documents, streamlining the permitting processes, consolidating multi-project bidding activities into one, and optimizing use of

**FIGURE 3**  Typical CFRP joint details at the bell (A) and spigot (B) ends

![Diagram of CFRP joint details](image-url)

**Source:** Image reproduced with permission from Fyfe Co. LLC, San Diego, Calif.

CFRP—carbon fiber reinforced polymer, GFRP—glass fiber reinforced polymer, Max.—maximum, NTS—not to scale, SSPC SP-10—Society for Protective Coatings industry standard for the preparation of steel surfaces, Typ.—typical
resident engineers and field inspectors during the construction phase.

Furthermore, a programmatic approach provides the flexibility to
address highest-priority pipelines early in the rehabilitation process. Rehabilitating low-priority pipelines may be postponed, which reduces near-term funding requirements. The approach also provides a framework to appropriately plan for funding requirements, which minimizes the variability of funding needs from year to year. The predictability and stability of funding requirements can help facilitate annual budget approvals by the utility board.

CONCLUSION
Condition assessment programs are often implemented as the result of a catastrophic failure or perceived emergency. Since the failure of its 102-in.-diameter PCCP in 1996, Providence Water has worked to improve the quality and durability of its installed systems by employing a proactive and programmatic approach to pipeline asset inspection and repair. Other utilities in the region and in other parts of the country have adopted a similar approach.

Overall, the industry is trending toward a more proactive approach to asset management, especially in the case of critical pipelines. The approach adopted by Providence Water demonstrates the effectiveness of a comprehensive, well-planned condition assessment and pipeline repair and rehabilitation program. The success of this approach is reinforced by the fact that no further breaks have occurred on the system since the program’s inception. The approach used by Providence Water can serve as a model for other utilities that are facing similar challenges and are looking for cost-effective approaches to manage their critical infrastructure.

Several million dollars have been spent on this asset since the late 1990s in a proactive inspection and repair approach, significantly less than if the pipe had been run to the point of failure and required emergency response.

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