Prestressed Concrete Cylinder Pipe Rehabilitation, Repair, and Replacement: Large Diameter Success Stories

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With ever increasing pressure on the "bottom line" performance of water utilities, many municipal managers, engineers, and operators are dealing with challenges presented by an increasing number of prestressed concrete cylinder pipe (PCCP) failures stemming from faulty pipe manufacturing from the mid-1970s to the mid-1980s. Type IV prestressing wire in PCCP pipe from that era has been identified as a prime culprit in many high profile, catastrophic failures, and continues to be the focus of condition assessment, corrosion monitoring, and renewal efforts intended to preempt additional failures.

This article focuses on the planning and construction activities that have been designed to expedite getting these pipelines back into service quickly, with the least disruption to utility customers and the general public.

Background

Prestressed concrete cylinder pipe (PCCP) was developed in the 1940s as an alternative to heavier reinforced concrete pipe (RCP) for larger diameters (above 30 in.) and to compete with ductile iron and steel products in water, sewer, and some stormwater applications. The PCCP has the following two general types of construction: a steel cylinder with a concrete core, or lined cylinder pipe (LCP), and a steel cylinder embedded in a concrete core, or embedded cylinder pipe (ECP). In either type of construction, manufacturing begins with a full-length welded steel cylinder. Joint rings are attached to each end and the cylinder assembly is hydrostatically tested to ensure water tightness. A concrete core is placed by centrifugal process, radial compaction, or vertical casting. After the core is cured, the pipe is helically wrapped with high-strength wire. The wire spacing is accurately controlled to produce a predetermined residual compression in the concrete core. The wire is sprayed with a thick cement slurry and coated with a cement-rich dense mortar coating.[1] Per the current American Water Works Association (AWWA) standard C301, the wire gauge must be a minimum of 0.192 in, with a wire wrapping stress exceeding 199,000 psi. The LCP products normally range in diameter from 16 in. to 60 in., with installations as early as 1942, and ECP, from 30-in. to 256-in. diameters, being applied since 1953.

In the early 1970s and continuing through the 1980s, a thinner gage of wire began to be used in manufacturing PCCP. This Type IV wire, because of its narrow gage (0.162 in or No. 8 gage) and "detrimental strain age" resulting from lack of temperature control during drawing operations, was more susceptible to hydrogen sulfide (H_2S) embrittlement from exposure in wastewater, but also any corrosives that managed to make their way through the substrate, either externally or internally. Mass wire breakage resulted in loss of prestressing that maintain hoop strength. (Hoop strength below standards in AWWA C304 can lead to failure.) As a result, a number of large-scale failures began to be experienced within 15 to 20 years of installation, particularly in wastewater streams with high (>200 ppm) H_2S concentration, as well as "hot soils" with high chlorides and/or low resistivities, which compromised the passivating effect of mortar (with pH of about 13) on steel when the pH begins to fall between 9 and 10. (Steel can no longer be considered passive when the pH of the environment falls to between 8 and 10.)

Still, other failures have been reported at joints due to separation or alignment issues, improper tapping of pipe, and on pipe barrels with significant point loading and foundation bedding deficiencies. (By the 1984 edition of AWWA C301, Type IV wire had been excluded from the standard, along with requirements in ASTM A648 requiring additional wire strength tests precluding use of wire with low ductility or detrimental strain age.[2]) Because of the larger diameters that have made PCCP an attractive installation option, these failures have often resulted in both tremendous water loss, as well as property damage and safety concerns to the public.

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Condition assessment of PCCP assets has progressed significantly over the last 15 years, with a number of technologies designed to detect wire integrity, either as broken strands or strands that have fractured and are slipping through the pipe substrate, as well as leaks. The experiences of three utilities that have addressed pipes at diameters 60 in. and above, in part due to both instances of failure and pro-active investigation and remediation to prevent failures, are presented.

Lake Tawakoni Pipeline Repairs Construction Management, Dallas Water Utilities

The Lake Tawakoni 84-in. raw water transmission main was completed in 1974 (with modifications in 1979-80) as an additional source of water for Dallas Water Utilities (DWU) following construction of the original 72-in. raw water supply main in the 1960s. It feeds the East Side Water Treatment Plant (WTP) just east of Dallas. As a result of several failures experienced on the older 72-in. line, DWU began a program of condition-based assessment that would eventually examine segments in both lines, annually looking for evidence of distressed pipe. The Pressure

Continued on page 6

Continued from page 4

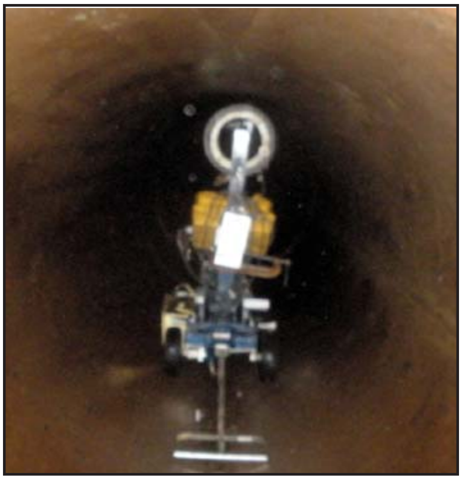
Pipe Inspection Co. (PPIC)—acquired by Pure Technologies in 2010—was commissioned in 2004 to assess both pipes. The PPIC employed remote field eddy current/transformer coupling (RFEC/TC) technology to inspect nearly 15.9 mi of pipe (0.03 mi of 72 in., with a balance of 84 inj) from near the East Side WTP toward the Interim Reservoir. The RFEC/TC is one of a group of electromagnetic (EM) technologies and is a form of nondestructive testing (NDT) for pipelines that uses the process of inducing electric currents/magnetic fields, either inside or on the surface of a pipeline, to measure an electromagnetic response. By creating these fields, defects inside the wall of the pipeline can be measured by analyzing the specific electromagnetic signatures produced. [5]

The pipe was isolated from the system as the WTP could be fed by an alternate raw water main and the dewatered pipe was inspected in the opposite direction of flow. The 72-in. line exhibited no breaks detected by the RFEC/TC, but of the 4,223 pipe segments (nominal 20-ft pipe sticks) inspected on the 84-in. line, 285 (6.75 percent) contained wire breaks ranging from five to 215 wire breaks per segment.[3] Of note is that none of the pipe had electrical bonding ("shorting") straps. Both pipe diameters were suspected to contain Type IV prestressing wire.

As a result of the RFEC/TC survey, DWU elected to replace 215 segments, which included pipes with 15 or more wire breaks per segment and adjacent pipes where there was little separation between distressed and non- or minimally-distressed pipes, as an economy of construction. Because pipe maintenance, including major repairs and replacement, is normally executed by DWU during the winter season (between October and May) when there was reduced system demand as well as limits on lake drawdown, it was decided to execute the project immediately following the inspection. The third-party construction management project included work designed by two separate design consultants and performed by three different construction contractors. The fast-track project (less than two months from start to substantial completion) included additional work scope that was also finished on schedule and under budget, while additional pipeline inspections and system upgrades during a rainy weather season in northeast Texas were undertaken. Replacement of pipe segments was facilitated by ECP and involved 10 to15 sticks of pipe at each mobilization. Repairs and rehabilitation to the pipe included full-joint replacement and external repair clamp installations based on the RFEC/TC inspections. Pipe removed during the pipe replacement operation was stockpiled for later investigation, and no additional forensics evaluation was undertaken.

Jacobs Engineering Group (Jacobs) served as construction manager for the emergency repair of the PCCP main. Jacobs coordinated the work of the design firms and provided management and administration oversight to the installing contractors. Value engineering was conducted throughout the design process, followed by reviews for biddability and constructability. Critical construction sequencing and supervision of night inspection crews on double shifts was also handled by Jacobs, in addition to special inspections, material testing, and project startup and close-out.

The DWU had not historically specified bonding joints or sacrificial anode beds as part of its corrosion control system on PCCP assets. However, geotechnical studies revealed "hotter" soils moving along the line westward toward Dallas that prompted DWU to do a corrosion study and design an



Crawler mounted RFEC/TC and video

Stepped excavation during PCCP replacement

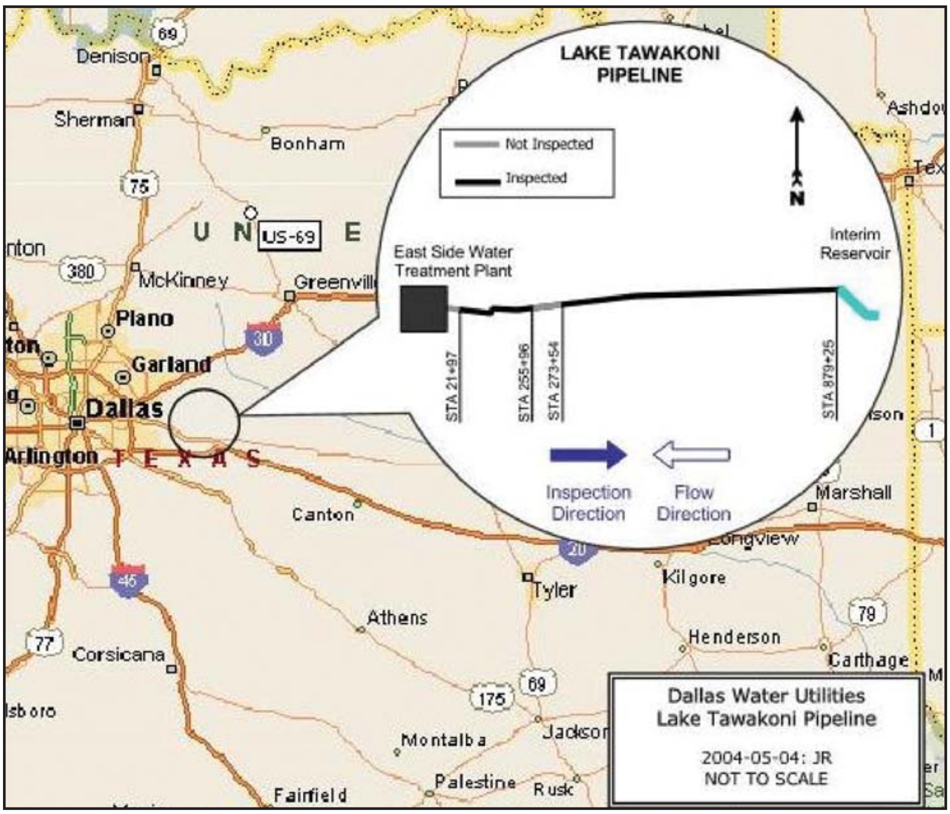


Figure 1. 2004 Lake Tawakoni Pipeline Condition Assessment

active corrosion protection system, which included cathodic protection. A subsequent inspection by PPIC was conducted in 2008 that re-analyzed and revised data from the 2004 study based on updated technology and the construction completed in 2004. The results indicated a minor increase in the number of distressed pipes in the previous inspection; about 10 percent of the previously diagnosed distressed pipe exhibited an increase in wire breaks over the four-year period, up to 55 more breaks in one segment. The 2008 effort also extended RFEC/TC inspection of the raw water main from the Interim Reservoir eastward to Lake Tawakoni, nearly 14.6 mi, with almost all 84 in. of pipe. Of the 3,997 segments inspected on the 84 in. of pipe, 7.1 percent were found to be distressed, with 7 percent of that amount having 25 or less wire breaks per segment. Although only six sticks of 72 in. were inspected, one pipe segment exhibited up to 50 wire breaks.[4]

The DWU is continuing to look at nonreplacement options for the Tawakoni line, in addition to replacement in areas that lend themselves to open-cut construction with minimal site and traffic impacts. These renewal options include slip lining with welded steel liners, carbon fiber-reinforced (CFR) liners, and other structural and semi-structural liners, including cured-in-place pipe (CIPP).

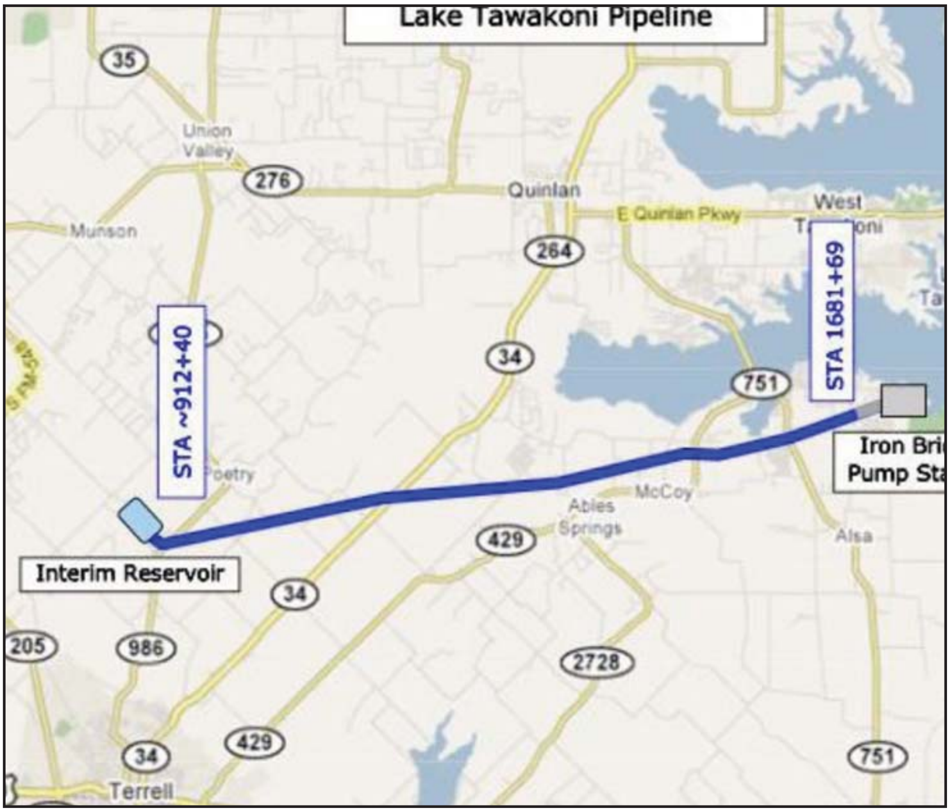


Figure 2. 2008 Lake Tawakoni Pipeline Condition Assessment

Vehicle-sized hole in 60″ PCCP

Broken prestresssing wires

Water Transmission Main, Louisville Water Company (Kentucky)

Since the early 1980s, Louisville Water Company (LWC) has had an aggressive program of assessing, repairing, or replacing its distribution mains—those generally classified below 20 in. in diameter. When a 60-in. transmission main catastrophically ruptured in March 2009, leaving a truck-sized opening in the side of the pipe, LWC quickly mobilized a team to investigate the causes.

The LWC contracted with PPIC and Jacobs to perform a nondestructive condition assessment of approximately two miles of 60-in. diameter PCCP and manage the repairs of the immediate collapse. The failed PCCP was installed circa 1973-74. The PPIC used RFE/TC technology to look for signal anomalies that might indicate broken or damaged prestressing wires inside the pipe wall, in addition to tractor-mounted video (CCTV) of the interior surface once the pipe was dewatered. With assistance from a specially equipped group of climbers trained in the Rocky Mountains, the team manually maneuvered its diagnostic equipment along the steep grades of the water main. The initial investigation revealed several possible locations with deficient wires.

The pipe locations, with the more obvious deficiencies (determined by the visual and RFE/TC reconnaissance,) were excavated and examined. In each instance, the location of either partially or fully deteriorated wires was pinpointed. At the failure site, less than 25 percent of the LCP was left intact and appeared to be in compression, showing actual wrinkles in the metal. This section of main was on a fairly steep grade and the line may have been pulling apart and sliding down the hillside. Wires that were inspected visually appeared to be in good to excellent condition with very little corrosion.

The damaged areas were patched with cement mortar, fitted with external steel collars (or tendons), and fully encased in cement rich grout.

Continued on page 8

Continued from page 7

Other project aspects included:

- *On-Site Project Management* – Realizing the magnitude of the damage caused by the pipe failure and the urgency to return the pipe to full service, LWC contracted with Jacobs to fulfilled the role of on-site project management. As such, numerous subcontractors and vendors were coordinated during the emergency repair.
- *Attention to Valves and Pipe Access* - Gearboxes were replaced and position stops adjusted on three 60-in. butterfly valves, double disc valve seats were re-bronzed to achieve leakproof shut off, and boiler plate manhole gaskets and bolts were replaced.
- *Rapid Return to Service* – Drawing on decades of experience, including more than 25 years with LWC, the 60-in. main was made fully operational within seven days of the initial failure. This included dewatering the entire 10,000 ft of pipe with a series of sump pumps, the nondestructive investigation led by PPIC, manning entry inspection, installing 100 ft of new main in the area of the blowout, disinfection via sodium hypochlorite (NaOCl), and dechlorination of the hyperchlorinated water from the reconstructed and adjoining pipe before discharge.

Subsequent "robotic" investigations of an additional 8.8 mi of the transmission main have also been completed by LWC. Instead of dewatering millions of gallons of treated water from the pipe exposing LWC and its customers to revenue loss and impacting other costs, PPIC implemented its electromagnetic device known as "PipeDiver" in the live, operating main.

The EM inspection technology-onboard PipeDiver functions much in the same way as a radio transmitter and receiver. The transmitter produces an EM field. The prestressing wires in the pipe amplify the signal that is recorded by the receiver. If there are broken wires, the signal is distorted; a measurement of the distortion quantifies the number of broken wires.[5] PipeDiver is an articulated, "free swimming" device, meaning it does not required tethering and travels in the direction of pipe flow, navigating certain types of valves (fully ported ones like gates, balls, and plug, and butterflies with sufficient clearance) and pipe bends in applications 24 in. and up. The LWC is now exploring other technologies, especially focused on its transmission assets above a 20-in. diameter, such as CFR and other structural and semi-structural liners, which can be applied rapidly in an urban setting with minimal disturbed footprint.

Finished Water Main Condition Assessment and Repair, Cobb County-Marietta Water Authority (Georgia)

A flow test of the underdrain system and subsequent fluoride tracer study in 2007 at the Cobb County-Marietta Water Authority (CCMWA) 105-mgd James Quarles Water Treatment Plant (WTP) north of Atlanta, was the first indication of a potential leak in the finished water system at the plant. During unrelated construction in 2010, excessive amounts of apparent groundwater were encountered, leading CCMWA to suspect a leak in one or more of the large-diameter pipelines crisscrossing the plant site.

A man-entry inspection, which included photographic evidence, of an 84-in. PCCP-finished water line revealed a circumferential break in the pipe near a bell and spigot joint between the existing finished water clearwell number 1, and a future clearwell, number 2. The failure was widest at the pipe's crown and ran to the springline on both sides. The proximity of the crack led the inspectors to suspect the weld at the bell ring had failed due to possible point loads during installation. Hairline circumferential cracking was also found

Continued on page 10

Steel tendon installation on PCCP

Pipe-Diver Free Swimming Tool

Inspection of PCCP Joints

Injecting internal seal adhesive

Completed internal seal installation

Measuring joint deflection in 54 in. pipe

Continued from page 8

within 6 in. of each joint within about a 180-ft span of the 84-in. main, as well as north of a 84-in. x 84-in. x 84-in. tee between the clearwells. Unlike the previous two case studies, this pipe was a relatively new installation, having been put into service in 2001.

Given the fact that the pipe in this area was constructed using restrained joints, and this segment of pipe was not subjected to high pressures at approximately 24 pounds per sq in. gauge (psig), it was considered a fairly low risk for total failure. The utility's immediate concern was to stop the leak to prevent further damage to the pipe itself, stop the water loss, and return the pipeline to service as soon as possible to meet customer demand and the construction schedule.

An internal joint seal was determined to be an acceptable solution, and Miller Pipeline Corp. was retained to install an internal joint seal (WEKO-SEAL®) to repair the pipeline. The internal joint seal is a flexible rubber, internally applied, leak clamp that ensures a noncorrodible, bottle-tight seal around the full inside circumference of the pipe-joint area. This type of seal is routinely used for sealing leaks at pipe joints; however, its use in this instance away from the joint was considered an appropriate application. The rubber seal is held in place with stainless steel rings that are jacked tightly against the seal, forcing it against the pipe wall.

In this installation, an extra-wide seal was used. It was held in place with four individual stainless steel bands. The installation process routine was fairly simple and consisted of the following steps:

- The joint or crack was packed with hydraulic cement to eliminate voids behind the rubber seal.
- The pipe wall was coated thoroughly with a food-grade lubricant.
- The seal was centered over the joint or crack.
- The stainless steel bands were jacked into place on either side of the seal.
- An air test was performed to assure a tight seal between the pipe wall and the rubber seal.

About 900 lin ft of the 84 in. was surveyed internally and one joint seal applied. Similar deflection issues were evident in a 54-in. ductile iron pipe (DIP) segment that connected to the 84-in. PCCP; after joint deflection and gasket positions were verified in a 300 lin ft run, three internal joint seals were applied. The leaks and associated soil foundation erosion appears to have been halted in both pipes.

Conclusions

Construction of water and sewer lines with PCCP continues to be a popular option among many utilities because of its resistance to physical damage, corrosion resistance, ability to tolerate high internal pressures as well external loading, and wide range of diameters. The American Concrete Pressure Pipe Association (ACPPA) reports that 90 out of the 100 largest water utilities in the U.S. use PCCP in their water systems, and the demand for PCCP is steadily increasing for transmission pipelines. Over 107,000,000 lin ft (over 20,300 mi) of PCCP has been installed in the U.S. and Canada, according to ACPPA. Forensic studies have indicated that PCCP has the lowest water main break rate per 100 KM, compared to other pipe materials in the same application.[6]

When PCCP does fail or begins to show signs of distress, several investigative technologies are available to determine where problems are occurring, or may occur, in future prestressing wire related events. Where manned entry and direct visual inspection aren't possible, these technologies can "listen" for wire-related events, or detect, through EM means, discontinuities in wire wraps indicative of breaks. While there are a range of rehabilitation and repair options available, sometimes straight replacement generates the lowest life cycle cost, especially when the costs of access to pipe, site preparation/restoration, and maintenance of traffic are included. Often, localized repairs, such as internal joint seals, make more sense when cracking is minor than large relining efforts, which require costly mobilization.

A primary driver for any renewal effort is generally how quickly the line can be put back in service, based on the scale of a project. Prioritizing segments that can be managed during a scheduled shutdown may also drive replacement, versus repair or rehabilitation. Utilities are beginning to adopt service standards, like DWU, where the frequency of wire breaks per segment, or over a defined alignment length, triggers further investigation, setting aside capital or operations and maintenance funds and scheduling renewal projects.

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