Technologies to Assess and Manage of Providence Water’s 102” PCCP Aqueduct

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Abstract

In 1996, Providence Water experienced a catastrophic failure of its 102” PCCP aqueduct pipeline. Subsequently, the main underwent an extensive assessment and repair and was returned to service with plans that the main would be re-inspected in approximately 5 years.

In 2005, Providence Water re-inspected the aqueduct. Since the previous inspection, the state-of-the-art for assessing PCCP mains has progressed significantly. Non-destructive technologies available for assessing and monitoring PCCP pipe have made significant strides. Providence Water implemented state-of-the-art inspection procedures to obtain the best possible assessment of the aqueduct. Following the assessment of 4.5 miles of the aqueduct, Providence Water opted to install a fiber optic acoustic monitoring sensor to continuously monitor the condition of the aqueduct and identify pipe sections experiencing ongoing wire break activity.

Providence Water utilized the following technologies during the most recent 2005/2006 inspection/monitoring program:

- Electromagnetic Inspection- to detect wire breaks in the prestressing wire
- Visual and Sounding Inspection- to inspect for cracks or delaminations
- Resistivity Testing- to determine the actual number of wire breaks on excavated pipe sections (vs. the estimated number based on the electromagnetic inspection)
- Acoustic Monitoring- to detect future wire breaks as they occur in the operational aqueduct

Following the initial inspection, one pipe section was found to be in a state of incipient failure. As a result, several nearby pipe sections were strengthened and a decision was made to install the acoustic monitoring system. This paper focuses on the assessment and monitoring technologies used during this project and describes the capabilities and limitations of these technologies.
Providence Water Supplemental Tunnel and Aqueduct (STA)

Providence Water operates a 9.5 mile tunnel/aqueduct system to convey potable water from a treatment plant to the distribution system. This system is one of two aqueducts that together deliver an average of 70 mgd of water from Providence Water’s sole treatment plant source to the many towns and municipalities which it serves.

The aqueduct portion of the STA was constructed in the 1960’s and consists of a 5.0 mile long 102-inch prestressed concrete cylinder pipeline (PCCP) and a 3.8 mile long 78-inch PCCP. The remainder of the STA consists of reinforced concrete tunnels and shafts.

The portion of the STA addressed by this paper is the 102-inch PCCP section. This portion of the aqueduct was built in the late 1960s. Its design included 15 different pipe classes with a core thickness of 6.5 inches. Prestressing wire pitch varied from 15 to 30 wraps per foot. The pipe consisted of both mortar coated and concrete coated pipe sections. The pipe was supplied by the Interpace Corporation, but predates the Class IV wire issue, as the wire used was Class II.

Failure of the 102-Inch Aqueduct and 1998 Inspection

On November 17, 1996, a section of the 102-inch aqueduct ruptured due to corrosion, leaving several communities with limited potable water supply until repairs were completed. The pipe that failed had a concrete coating and it is believed that the coating separated from the concrete core exposing the prestressing wires to a corrosive environment.

In 1998, an internal inspection was performed of the 102-inch aqueduct to assess its structural integrity. This inspection utilized state-of-the-art inspection techniques at that time and relied on visual inspections, hammer soundings, and impact echo testing. The inspection identified several pipe sections which had loose portions of concrete coating. This inspection led to the carbon-fiber repair of 27 pipe sections, one of the first applications of carbon fiber repair in PCCP.

Following the inspection and repair work, it was decided that the main would be re-inspected in approximately 5 years.

Figure 1: 1996 failure of 102-inch PCCP aqueduct and 1998 carbon fiber repairs
Providence Water Inspection 2005/2006 Program

Providence Water initiated the re-inspection of the aqueduct in 2005. Similar to the 1998 inspection, the assessment was to use state-of-the-art assessment tools for PCCP. However, techniques to assess PCCP had progressed significantly since the previous inspection and it was decided to use other techniques during the 2005/2006 inspection program. During the execution of the inspection, the following assessment techniques were utilized:

1. Electromagnetic Inspection
2. Visual and Sounding Inspection
3. Resistivity Testing
4. Acoustic Monitoring

All of the techniques are generally focused on ascertaining assessment data on the condition of the prestressing wire, the component of the pipe that provides its strength and that can be vulnerable to corrosion.

*Electromagnetic inspection* is a non-destructive testing technique that involves traversing the interior of a pipeline with equipment that can electromagnetically test the condition of the prestressing wire wrapping in a PCCP. An electromagnetic field is induced on the prestressing wire on one side of the pipe. Using the prestressing wire, this field is transmitted to the opposite side of the pipe where it is measured and recorded. The data is then evaluated to identify electromagnetic anomalies consistent with wire breaks in the prestressing. These anomalies are further evaluated, to determine the spatial characteristics of the anomaly and estimate the length of damaged pipe and number of wire breaks.

*Visual and sounding inspections* are non-destructive techniques which involve visually inspecting and sounding the interior pipe wall for evidence of a loss of prestressing in a pipe. Certain types of cracks are indicative of a loss of prestress, which is an indication that the pipe section has significant wire break damage. The sounding portion of the inspection involves tapping the interior surface of the pipe with a hammer or bar to listen for “hollow areas” indicative of a delamination. Delaminations are often associated with significant wire break damage.

*Resistivity testing* is a technique that can be used on an individual pipe section to ascertain an accurate number of wire breaks for that pipe section. It requires an excavation to the crown of the pipe and a chipping hammer to expose the prestressing wire. A resistance meter is then used to measure the resistance of a prestressing wire loop(s). Intact wires have a low resistance, but
where a loop has an abnormally high resistance value, the loop is broken. This is an accurate method of determining the number of wire breaks on a particular pipe section. Subsequently, the pipe is patched with mortar.

*Acoustic monitoring* is a non-destructive monitoring technology that relies on continuously monitoring the acoustic activity propagating through a pipeline to identify the acoustic event associated with a breaking wire (identifying the snapping sound). This technology provides the time and location of wire breaks for a pipeline and is useful for determining which pipe sections are experiencing active wire break activity and what the rate of activity is (i.e. number of wire breaks on a pipe section per month).

**Execution of the Inspection**

For logistical reasons, the inspection of the 102-inch was broken down into two sections. A 4.5 mile portion of the aqueduct was inspected in October 2005 and a 0.5 mile portion was inspected in December 2006. The inspection personnel consisted of two teams: an electromagnetic inspection team (Pure Technologies) and a visual and sounding inspection team (CDM). Both teams traversed the pipe together.

For the 4.5 mile inspection, the electromagnetic inspection team pointed out suspected electromagnetic anomalies indicative of wire break damage as the data was gathered. Although reliably identifying anomalies requires a more detailed analysis, pointing out suspected electromagnetic anomalies during this first view gave the visual and sounding inspection team, the opportunity to closely inspect numerous pipe sections that were later confirmed to have electromagnetic anomalies consistent with wire break damage. For pipe sections suspected of exhibiting electromagnetic anomalies, the visual and sounding inspection team immediately performed a close-up visual inspection and hammer sounding.

**Pipe Section 5BH9**

Once the field work for the inspection was complete, the intent of Providence Water was to return the aqueduct to service. However, the inspection identified one pipe section, Pipe Section 5BH9, as having a serious problem. This pipe section was located in the vicinity of the 1996 failure.

During the electromagnetic inspection, 5BH9 had a significant electromagnetic anomaly consistent with wire break damage. An electromagnetic calibration for Providence Water’s transmission main was not feasible for the 102-inch STA. Calibrations provide data on the nature of electromagnetic anomalies caused by wire break damage and improves the accuracy of the data analysis and results. Without a calibration, Pure Technologies relied on past calibrations and inspection experience for similar pipes to evaluate the Providence electromagnetic data. This analysis indicated that there was an area of wire break damage, consisting of approximately 45 wire breaks, located approximately 4.2 feet from the upstream joint.
During the visual and sounding inspection, a four foot long hollow area was identified on this pipe section. There were no cracks visible on the pipe section. The hollow area did not match with the location of the electromagnetic anomaly as it was located in the quadrant of the pipe closest to the downstream joint.

Given that this pipe section exhibited an electromagnetic anomaly and a significant hollow area, it was recommended that the aqueduct not be returned to service until the pipe was further evaluated and repaired. The pipe was then excavated and the exterior of the pipe was sounded. Nearly the entire length of the coating on one side was hollow. The coating was removed and numerous wire breaks were observed. In fact, the pipe section had more broken wire wraps than intact wraps and the pipe section was obviously in a state of incipient failure. This pipe section was repaired with post-tensioning tendons. Furthermore, given the close proximity of this pipe to the 1996 failure and the relatively high consequence of failure in this area of residential homes and apartments, it was also decided to carbon fiber repair seven pipe sections in this area.

One of the interesting findings on Pipe Section 5BH9 is that the electromagnetic anomaly for this pipe section appeared at the location of intact wires instead of broken wires. This electromagnetic phenomenon can occur when there is extensive wire break damage on a pipe section. Therefore, as was the case with Providence Water, it is usually advisable to combine electromagnetic inspections with visual and sounding inspections. The two inspection techniques are complementary and address limitations in each technique.
Other Pipe Sections with Electromagnetic Anomalies

Besides 5BH9, there were 50 other pipe sections that were identified to have electromagnetic anomalies consistent with wire break damage. Wire break estimates on individual pipe sections ranged from 5 to 70 wire breaks.

To provide calibration data for the electromagnetic inspection analysis and to determine the actual condition of several at-risk pipe sections, Providence Water excavated twelve pipe sections initially reported to have electromagnetic anomalies to obtain the actual number of wire breaks through continuity testing. Based on this calibration data, it was determined that one class of electromagnetic anomaly was caused by a phenomenon other than wire break damage. Also, it was learned that the algorithms used to estimate wire breaks were overestimating wire break damage. Using this calibration information, the algorithms were modified, which resulted in a net reduction in the estimated number of wire breaks.

The original wire break estimation algorithms were based on PCCP with shorting straps. Shorting straps are used (primarily on the west coast) during manufacturing to make all wire electrically continuous for the provision of cathodic protection. However, the STA does not have shorting straps. At around the same time as the Providence inspection, several other calibrations on east coast pipes without shorting straps were performed, including Greater Lawrence Sanitary District (72-inch), Springfield, MA (60-inch), Washington Suburban Sanitation Commission (60 and 96-inch), and the City of Baltimore (54-inch). Calibration data from the STA is similar to these other calibrations and it has been learned that the effect of a relatively few number of wire breaks (e.g. less than 10) creates a relatively large (as compared to the amount of damage) electromagnetic anomaly. As damage grows from this point, the size of anomaly also grows and tends to approach a similar relationship for both types of pipe.
With the resistivity testing and calibration complete, it was concluded that a pipe section with 44 wire breaks had the highest wire break total. This total was arrived at through the resistivity testing and it was learned that the wire breaks were scattered along the pipe section. This pipe section and all other pipe sections were deemed to be at an acceptable level of risk, so it was decided that the 102-inch STA could be returned to service. However, given the past history on the main and that 50 other pipe sections have electromagnetic anomalies consistent with wire break damage, Providence Water opted to install a long-term continuous acoustic monitoring system to track the performance of the aqueduct.

**Long Term Acoustic Monitoring**

Acoustic monitoring systems for PCCP mains are available in a variety of configurations. The types of sensor and communication protocols vary, but all designs must continuously monitor acoustic activity in a pipeline to detect the acoustic event associated with a wire break.

For long term monitoring of long mains, fiber optic sensors are usually most cost effective. These sensors consist of four or more glass fibers bundled with a strength member and encased in a protective sheathing. The sensor is run along the invert of the pipe and attached to the pipe as required. A laser is used to project light down the fiber and a data acquisition system monitors reflections generated by the acoustic activity in a pipeline. The advantages of this technology are:

1. No electronics are placed in the water flow;
2. The entire fiber acts as a sensor, so the sensor is never further than a pipe diameter from a wire break;
3. Long sections of pipe (up to approximately 12 miles) can be monitored with one data acquisition system;
4. Monitoring system noise (e.g. electronic noise) is nearly eliminated.

For these reasons a fiber optic sensor was used to monitor the 102-inch aqueduct. The sensor was installed on the invert of the aqueduct and the main was re-charged. The wire breaks recorded by the acoustic monitoring system are now added to the estimated wire breaks determined by the electromagnetic inspection and thus at any point in the future, Providence Water can ascertain an estimated number of wire breaks on each pipe section. This total number of wire breaks can be entered into a structural analysis model and the risk associated with each pipe section can be calculated. If a pipe section deteriorates to an unacceptable level of risk, Providence Water can intervene to initiate a repair of the pipe section thus avoiding pipe failure.
Conclusions

Providence Water performed a state-of-the-art assessment of the 102-inch portion of the STA aqueduct and tunnel system. The assessment identified one pipe section in a state of incipient failure and 50 other pipe sections that had electromagnetic characteristics consistent with prestressing wire break damage. The pipe section near failure was repaired and the remaining pipe sections were deemed to be within an acceptable level of risk.

A long term acoustic monitoring system was installed in the aqueduct to monitor wire breaks into the future to provide a proactive management solution for Providence Water. The wire breaks recorded by this system are added to the wire break estimates calculated during the electromagnetic inspection results, which provides Providence Water with the ability to estimate how many wire breaks are on each section of pipe in near real time.

The implementation of these inspection techniques for Providence Water required an understanding of the fundamentals and limitations of each technology. The assessment program was successful because it was structured to use multiple assessment techniques to address the limitations of any single technique.