Rehabilitating a Life Line:
Inspecting and Repairing the Hultman Aqueduct in Metropolitan Boston

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Abstract

The Massachusetts Water Resources Authority (MWRA) provides water to over 2.2 million people and 51 communities serving greater Boston and central Massachusetts. They are undertaking a $57 million construction project to rehabilitate the 13.4-mile long, 11.5-foot diameter Hultman Aqueduct, including: inspection and repair of the existing aqueduct pipe and construction of several large diameter valve chambers to house connections between the existing Aqueduct and the new MetroWest Tunnel.

This paper will focus on the planning, inspection, and repair of the inside of the Hultman Aqueduct that has been completed to date for the first 10 miles. Because the Aqueduct could not be inspected and the exact extent of repairs quantified before the construction contract was awarded, a number of challenges needed to be considered.

Before construction was awarded, the MWRA and its consultant needed to develop an inspection plan before any entry into the Aqueduct could be performed. Unique aspects of inspecting this major structure included limited points of access (typically 2 miles between access points), the need for inspecting and making repairs while working inside confined spaces, and the need to implement the repairs in a timely manner all make this project challenging. The inspection required the MWRA's consultant and the contractor to work cooperatively together to conduct the inspection inside the Aqueduct to locate defects and problems that need to be repaired, devise practical repair details, and implement methods and procedures that will eliminate existing leaks and extend the useful life of the Aqueduct.

Introduction:

Today's aging infrastructure will need a lot of attention to rehabilitate it in a timely and cost effective manner. Large diameter conveyance systems can be expected to have a high rehabilitation cost. Because of their size, they also provide more opportunity for productive person-entry inspections that allow specific repairs to be located and completed that other smaller systems do not afford. As such, understanding how other similar systems have been repaired and what methods worked well and those that could be improved will be useful to all owners, engineers, and contractors that get involved with similar projects.

The MWRA is undertaking a $57 million construction project to rehabilitate the entire length of the Hultman Aqueduct. Since 1939 until recently, the 138-inch diameter Hultman Aqueduct has been in continuous service delivering almost all of the clean, treated drinking water to the Boston area. With other tunnel infrastructure just recently completed, the MWRA has, for the first time since it was put into service over 60 years ago, been able to inspect the inside of the Aqueduct and undertake repairs so that it can remain a viable and dependable component of their water delivery system.

This project includes inspection and repair of the existing aqueduct pipe and construction of several valve chambers to house connections to the new MetroWest Tunnel. The interconnections that are being provided between these two parallel conveyance systems greatly increase the redundancy of water supply to the Boston area leading to improved public health and safety. When work is complete, the Hultman Aqueduct and the new MetroWest Tunnel will operate together but can be used interchangeably. If either one needs repair, the other will be activated, with little or no interruption to service. Segments of each can be taken out of service while the other continues to convey water to Boston.

The Hultman Aqueduct was designed to be a pressure line operating under heads from 20 feet to 220 feet. It is 18 miles long, constructed primarily by cut and cover methods with a 3 mile long tunnel section. It is part of the transmission system to convey potable water from the state's reservoir at Wachusett Reservoir to metropolitan Boston area. The length of the Aqueduct considered in this paper is approximately 15 miles long. Figure 1 shows the extents of the Hultman Aqueduct.

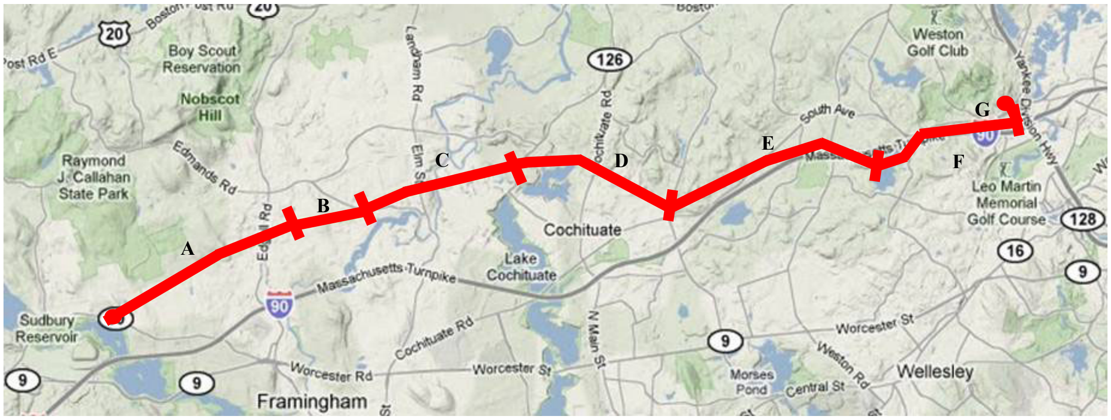

Figure 1 Hultman Aqueduct

The Aqueduct follows contour of the ground to avoid as far as was practicable costly excavations and fills. Some portions of the Aqueduct were constructed in man-made embankments up to 28 feet high with a crest width of 20 feet and side slopes of 1.75H:1V. The typical depth of cover over the Aqueduct was 2.5 feet. During construction through swampy areas, organic soils were reported to be removed and replaced with gravel and crushed stone.

The reach of the Hultman Aqueduct being rehabilitated today was constructed primarily of 16 foot long precast steel cylinder reinforced concrete pipe with a 11-foot 6-inch (138-inch) inside diameter. A limited reach approximately 2,300 foot long consisting of 84-inch diameter pipe is also included. The steel cylinder provides a watertight pipeline. Outside the steel cylinder are two cages of steel reinforcement covered by concrete to provide corrosion protection to the embedded steel. A 2¼-inch thick concrete mortar liner was placed inside the steel cylinder. Overall, the wall is 11-inches thick for the 138-inch diameter sections and 8-inches for the 84-inch diameter sections. Each section weighed 40 to 50 tons. The joints between sections were formed by bell and spigot of the steel cylinder. Figure 2 shows a typical cross section of the joint between pipe sections.

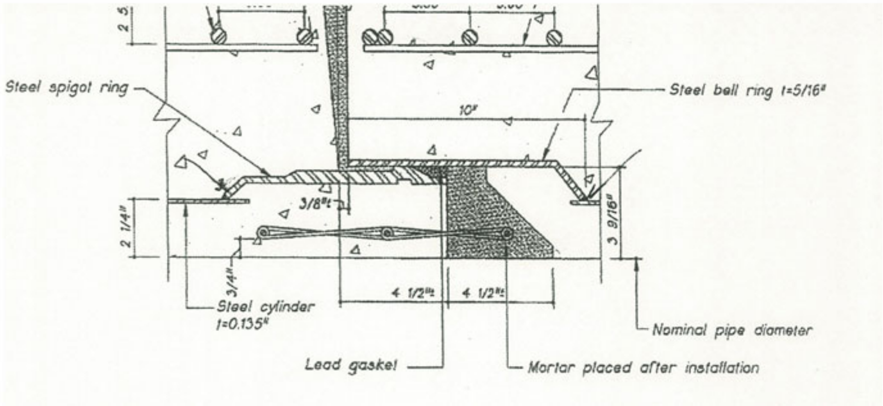

Figure 2 Typical Cross Section

A unique feature of this joint design was the lead gasket used to complete the joint. A lead joint was packed into the joint and a concrete mortar was placed to fill the joint section. The lead joint was packed into the joint by hand and by pneumatic methods. An article written in 1941 described this process and noted that either method appeared effective. The contractor's used both methods when the Aqueduct was constructed. After the lead joint was completed, the rest of the joint was filled with a mortar comprised of one part cement and two parts sand by hand placement or gunite process.

The Aqueduct was provided with manways for future access, air release valves at intermediate high points to facilitate filling, draining, and operation, and blowoffs at low points to allow drainage of the aqueduct. Some pumping is required to dewater the aqueduct for some isolated low points where it was not practical to provide blowoffs at the physical low point, for example when crossing below rivers and waterways.

Design Phase Considerations

At the start of design, a review of the available information helpful to understand the exiting condition of the Aqueduct was undertaken. This information included detailed record

Figure 3 Internal pipe identification

drawings developed in the 1940's. The record drawings included a plan and profile view that documented the stationing for each 16-foot pipe segment, the invert at each joint, the pressure rating, and a unique pipe identification number. Figure 3 shows a photograph of the unique number identifier for pipe 4-464 that although over 60 years old remained visible during the inspection today and that was helpful in correlating locations of specific defects with as-built pipe segments. In addition, the record drawings provided stationing to locate each of the 14 blowoffs and 62 manways and air release valve connections, and six smaller diameter connections to pump stations along the way. The records also indicated the day, month, and year that the specific pipe segment was installed. Records of concrete cradles, culvert crossings, and other features installed during construction are also detailed on the record drawings. These records were invaluable in all phases of the project to locate specific features inside the Aqueduct prior to beginning the inspection and during repair.

In the 1990s, the MWRA also undertook a leak detection program to locate potential leaks along the Aqueduct. The program identified 21 potential leaks reported over the life of the aqueduct that should be considered for future repair. Of these, only seven had visible water in the vicinity of the reported leak. Overall, this suggested the Aqueduct was in good condition considering its age and low frequency of reported leaks.

The MWRA also performed corrosion assessments of the Hultman Aqueduct in 1997 and subsequent testing in 1999. The 1999 work included uncovering the outside surface of the Aqueduct at 10 locations for visual observation of possible corrosion observations, visual inspection of the embedded steel reinforcement, Schmidt hammer testing to estimate concrete strength, testing to estimate the depth of any potential carbonation, and testing to detect active corrosion cells between the wet concrete surface and steel reinforcement. At each location, there were no signs of reinforcement corrosion or concrete cracking, and the pipe surface showed no sign of corrosion. The average compressive strength of the concrete pipe wall ranged from 4,100 to 6,300 psi. The depth of carbonation did not exceed 1/8th inch. Overall, the concrete surface of the Aqueduct appeared in excellent condition in all but one site, where scaling was observed to a depth of 1/8th inch.

During construction of the MetroWest Tunnel, the MWRA had an opportunity during a brief period to inspect a limited portion of the Hultman Aqueduct. In April 2004, the MWRA conducted inspection of an upper (or western) portion of the Hultman Aqueduct approximately 2 miles long beginning at the Carroll Water Treatment Plant and ending at Shaft 1. The inspection covered 790 pipe segments. The inspection was completed in two days and followed by two days of non-destructive testing using impact echo and two days of surgical destructive testing. The report prepared from the 2004 inspection provided valuable information that formed the basis for inspection of the remaining 13 miles as well as development of repair strategies for the entire length of the Hultman Aqueduct.

The inspection found that the upper Hultman Aqueduct is in excellent condition and the joints, with the exception of a few which have circumferential cracks at a distance of 4 to 8-inches from the joints, are also in excellent condition with no cracks and no offset. It included estimates of the circumferential cracks near joints that occurred at approximately 6% of the total number of joints. The results also indicated the outer reinforced concrete core is not cracked and that there was no corrosion of the steel cylinder. Although non-destructive testing using impact echo indicated some cracking of the outer core concrete, upon examination of subsequent surgical destructive testing, no cracking was indicated. At all pipe locations evaluated for destructive testing, the exposed surface of the steel cylinder consistently showed no signs of corrosion or oxidation, and the exposed inner surface of the outer core consistently showed no signs of cracking of the concrete. Also, petrographic examination of core samples showed the concrete to remain in excellent condition. The results of core samples indicated observed cracks formed during the manufacture of the pipe and not during installation or operation of the Aqueduct.

Hultman Aqueduct facilities that could be inspected without having to physically enter the Aqueduct were inspected over the period of December 2005 to June 2006 and a report documenting the findings was prepared. The surface inspection was carried out by walking and/or driving the length of the Hultman Aqueduct and documenting pertinent information. The relevant aspects of the external inspection considered in preparing the internal inspection plan included a review of the topography along the Aqueduct alignment (areas with steep change in grade), stationing at locations where the Aqueduct intersects streets and roadways that could be used to access and egress for the internal inspection of the Aqueduct, locations where standing water exists above the Aqueduct (swamp, creeks, river, etc), locations and dimensions of manholes to determine if they were functioning properly and if it could be used for access/egress and ventilation portals during the internal inspection, and potential locations for discharging water from the Hultman Aqueduct through existing blow-off valves.

During the design phase, the MWRA also wanted to observe the existing condition inside the Aqueduct to provide a qualitative assessment of its condition. They conducted a closed circuit television inspection with entry at 16 locations. The purpose of the inspection was to document the condition of the interior of the pipe in these areas accessible.

This inspection was performed in December 2006 and covered 6.3 miles. The inspection was conducted using a truck mounted camera mounted on an small tractor unit. The camera and tractor assembly were lowered through man ways at the designated sites and were recorded on DVD. The overall condition of the aqueduct was observed to be in very good condition. In the main barrel sections only minor leaks were found and were identified by mineral deposits on the pipe surface.

After compiling the available data and past reports and records of the Aqueduct construction and existing conditions, the MWRA prepared an estimate of the likely defects and repairs to be anticipated. The available data suggested that cracks of the mortar liner, spalling concrete, and possible corrosion of the steel liner were the primary pipe repairs that would be needed.

The frequency of defects observed in the previous inspection of the upper Hultman Aqueduct was used to develop estimated quantities of repairs for the 13 miles considered in this project. For example, the previous inspection estimated crack repair at 6% of the pipe joints. This was used as an estimate of the frequency for crack repair in the downstream 13 miles. With the estimated quantities in hand, estimated construction costs were developed taking into account the affects the limited access and slower production working within the confined space would have on the cost of the repair work.

Circumferential cracks less than 1/16” would be left alone unless visible leakage was observed. Circumferential cracks wider than 1/16” would be repaired by saw cutting and filling with an NSF 61 approved epoxy adhesive in accordance with the manufacturer’s written instructions. Spalled concrete liner was planned to be removed and replaced with new cement mortar meeting current AWWA standards. In a limited number of cases, a certain amount of steel pipe liner was expected to be found corroded and needing to be replaced. A typical detail calling for welding a steel patch over such areas was developed as one approach for this type of repair. The unit price for such welding included costs for ventilation and air monitoring in the confined space.

A work plan was developed for the internal inspection and included in the bid documents that described the delegation of work the MWRA, contractor, and consultant would perform during construction to locate defects inside the Aqueduct. The work plan included a concise objective and background information of the information available during the design to determine the extent of the inspection work and a summary of the previous inspections completed.

An important aspect of developing the work plan was to select access points that were accessible, provided reaches to be inspected and repaired from two ends whenever possible, and to maintain a maximum length between access points that can facilitate labor, material, and equipment transport. As such, the work plan for this inspection included a description of the individual reaches that were to be inspected and how they were selected and whether it was expected to be completed using a motorized inspection vehicle or walking the entire length of the Aqueduct. It also included the types of testing anticipated for the inspection such as non destructive and surgical destructive testing at limited areas along the Aqueduct. A schedule describing the overall duration in days to be allocated in the contractor’s schedule for the inspection was also stipulated.

As for any inspection, safety of those inspecting the Aqueduct was of paramount importance. The safety program must comply with OSHA 1926.800 that governs underground construction. The contractor must also remain responsible for safety since they are most in control of the activities ongoing during inspection and repair. But, minimum criteria should be set to provide a basis for the contractor to provide a reasonable bid price for the inspection support and to be clear that the contractor's safety plan must cover their labor as well as those of the owner and consultant that need to enter to perform and monitor the inspection and repairs.

The work plan included requirements for the general confined space entry activities that would be followed for each entry and the assignment of roles and responsibilities for the inspection personnel. A generalized hazard assessment identifying expected hazards and minimum personal protective equipment (PPE), air monitoring, and procedures that the inspection team would follow to mitigate the hazards was included. The work plan also set specific requirements for the contractor to provide adequate number of trained personnel and equipment for monitoring, safety, and potential emergency evacuation. The contractor was required to finalize its confined space entry plan based on this specification format.

Table 1 summarizes the reaches inspected, the lengths of each reach, and the maximum grades that the inspection vehicle and inspection personnel needed to negotiate from inside the aqueduct. Due to the length of the sections of the Aqueduct being inspected, and the need to walk portions of the inspection, a separate access/egress location was typically provided when possible to enter and exit each section. The existing manways provided mechanical ventilation and lighting as well as means for the top side support personnel to communicate with the inspection personnel as they passed. The contractor was also responsible for coordinating with the local emergency response personnel to assist for emergency rescue if needed.

Table 1 – Summary of Inspection Reaches

Segment	Length (Miles)	Reach Description and Maximum Grade
A	2.42	Shaft 4 to Grove Street Max Grade 22 degrees Motorized Inspection Vehicle
B	1.84	Grove Street to Brooks Street Max Grade 15 degrees Motorized Inspection Vehicle
C	1.07	Brook Street to Valve Chamber L2 Sudbury River Crossing Max Grade 13 degrees Motorized Inspection Vehicle
D	2.90	Valve Chamber L2 to Rice Road Max Grade 6 degrees Motorized Inspection Vehicle
E	2.52	Rice Road to Valve Chamber N2 Max Grade <6 degrees Motorized Inspection Vehicle

Table 1 – Summary of Inspection Reaches

Segment	Length (Miles)	Reach Description and Maximum Grade
F	1.66	Valve Chamber N3 to Bifurcation Max Grade <6 degrees Motorized Inspection Vehicle
G	0.49	Bifurcation to Valve Chamber 5A2 and the 84" Hultman Branch Line Inspection by walking only due to short reach and smaller diameter
Total	13.54	

The safety plan also required the MWRA and contractor to implement a mutual lock out/tag out (LOTO) program to eliminate potential release of hydraulic energy by inadvertently opening a valve. The LOTO program was effective at providing a double block for hydraulic energy sources for most cases.

Figure 4 shows one of the access points provided by removing one 16 foot section of the Aqueduct. At the completion of the inspection and repair work, a new reinforced steel pipe segment was replaced and the pipe backfilled to pre-existing conditions.

Figure 4 – Access Point (Transition from Segment D and E)

Construction Phase Considerations

Upon award of the construction contract, the contractor began preparing submittals relating to inspection. One of the first submittals was a proposed change to the bid documents that anticipated use of an electric vehicle. The contractor proposed use of diesel operated vehicles because they provided more power for negotiating the steep grades. This would facilitate the inspection and repair. The contactor was able to meet the OSHA 1926.800 requirements for ventilation based on the horsepower of the proposed equipment and the number of inspection and repair crews anticipated to be in the Aqueduct at one time. Figure 5 shows a picture of the inspection vehicle fitted with an inspection platform that was used to inspect the crown of the Aqueduct. Figure 6 shows the vehicle during inspection activities inside the tunnel.

Figure 5 – Inspection Vehicle

The entry team consisted of two inspectors (a lead inspector and one support inspector) provided by the MWRA's design consultant. The contractor's support team provided the three inspection vehicles and operators for each, top side attendants, the permit required confined space entry attendant, dewatering personnel and equipment to keep the Aqueduct drained and dry, mechanical ventilation systems, and other support personnel and equipment. In addition the contractor was responsible for monitoring air quality in accordance with the safety plan and be responsible for safety of all personnel whether contractor, owner, or consultant personnel while in the Aqueduct.

Attendants were stationed along the Aqueduct at the manways outside as the inspection team proceeded. These attendants were able to monitor the inspection as it passes. When the inspection team passed the intermediate manway, the attendant recorded the time and checked on inspector's conditions, and in turn could call the ground team supervisor and other attendants to report status.

Figure 6 – Inspector on platform

The internal inspection included a walkthrough inspection to identify the condition of bulkheads, pipe joints, differential settlement (areas of standing water), and joint openings, leak through joints and access manways and other ancillary features (e.g., condition of blow-off, manway, and pump station connections). Each pipe section was marked using an internal stationing system for use in recording conditions observed. Visual observations and soundings of the interior core (concrete lining and steel cylinder) were performed for indications of possible separation at the steel cylinder and lining interface. If areas were observed to have evidence of diagonal tension and flexural cracking, then impact echo NDT and additional surgical destructive testing may have been called for. However, no such conditions were observed.

Table 2 below summarizes the timeframe to inspect the various reaches to date. Overall, the inspection averaged approximately 1/3rd mile per day to mark out defects and identify repair types.

Table 2 – Summary of Inspection Duration

	Length	Cumulative	Days of Inspection			Miles Per Day
	(miles)	(miles)	Start	End	Total	
Segment A	2.41	2.41	11/30/09	12/8/09	7	0.34
Segment B	1.83	4.24	11/19/09	11/25/09	5	0.37
Segment C	1.24	5.48	11/16/09	11/18/09	3	0.41
Segment D	2.99	8.47	12/9/09	12/29/09	15	0.20
Segment E	2.51	10.98	12/30/09	1/14/10	12	0.21
Totals	10.98				42	
Average Miles per Day						0.31

In practice, the inspection found these reaches of the Aqueduct to be in similar condition to the upper section inspected previously. A photographic record was kept for each pipe joint before repairs, during and after, which is valuable to facilitate decision making. For the defects that were observed, many were similar to those originally anticipated when the bid documents were developed.

For example, the most frequent defect found was circumferential cracks less than 1/16" wide for which no work was recommended unless there was visual evidence of leaking. Numerous cracks wider than 1/16" were also observed and these could be repaired by widening the crack by saw cutting and filling with an approved product. Rather than filling with cement mortar, the repair product selected was an NSF 61 approved epoxy material.

In areas with spalled or cracked concrete liner where repair was required, the concrete was saw cut beyond the defective limits and removed by power chipper and hand tools when nearing the steel liner to avoid damage. After preparing the edges to be perpendicular to the steel liner, the steel liner and lead gasket was cleaned by non-mechanical means and inspected. The inspection was to observe any visual evidence of leakage through visible deterioration, gaps, or evident rust. A standard detail developed to represent repair of this type of defect is shown in Figure 7.

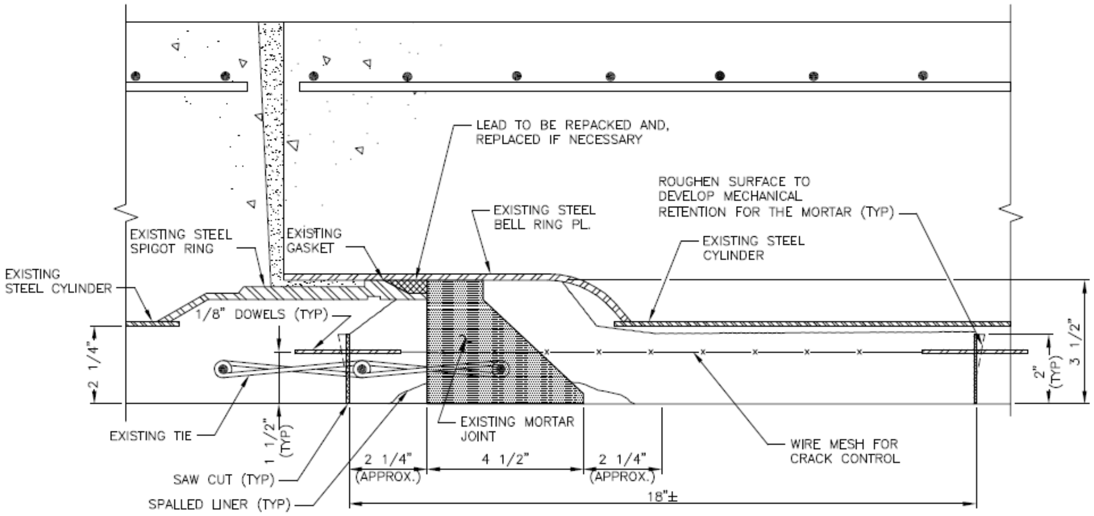

Figure 7

In other cases the type of repair was not as anticipated. For example, in lieu of welding steel plate to eliminate corroded sections of the steel liner, no such cases were encountered. Instead, repacking of the lead was found to be a more productive and cost effective means of cutting off water infiltration. The contractor was required to provide training for personnel performing repacking the lead gasket by an individual with a minimum of 15 years experience on lead gasket repacking for water lines in at least 10 projects totaling over 75 lead gaskets repacked.

If leakage through the gasket was observed, the limits to be repacked were agreed to between the contractor's field personnel and the owner's on-site representatives. It was then hand packed to eliminate the leakage before the mortar repair proceeded. The mortar repair was paid as a unit price based on the length of the repair. Because the amount of gasket repair could not be quantified until it was uncovered and observed for evident leakage, this activity was reimbursed on a time and materials basis with the Owner's inspection personnel recording the extent of the work.

The figures that follow show a typical joint selected for repair, the removed mortar at the joint can be seen followed by the repacking of the lead joint and observations for continued leakage in a progression showing the various stages of the repair in Figures 8 through 13.

At the completion of the repairs, the contractor removed all remaining material, transported it to the Aqueduct openings, and disposed of it legally. The repairs were inspected before closing a specific reach to be sure the repairs were free of defects including voids, segregation of materials, cracks, spalls, surface irregularities, etc.

In addition, the cast iron spool pieces used to connect the air release and manways in the aqueduct crown and the blow valves near the invert were cleaned from within the aqueduct by wire brushing and lined with an NSF 61 approved epoxy product.

Figure 8 - Active Infiltration Defect

Figure 9 - Mortar Liner Removed

Figure 10 - Lead joint repacking

Figure 11 - Observation for Leakage before Mortar Repair

Figure 12 – Complete Repair

Figure 13 – Mortar repair and original mortar interface

Conclusions

As noted in the introduction, today's aging infrastructure will need a lot of attention to rehabilitate it in a timely and cost effective manner. The inspection and repair of the Hultman Aqueduct provided a unique opportunity to plan, bid, and implement repairs to a large diameter conveyance system that required careful planning. The importance of developing a detailed work plan that anticipates the types of hazards that could be encountered and that mandates minimum requirements for safety, training, and monitoring was very helpful controlling the cost of this inspection and repair. When completed, this section of the Hultman Aqueduct will be ready to convey water to the metropolitan Boston area for years to come.