Structural Rehabilitation of the Kenilworth PCCP Transmission Main with Steel Slipliner

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ABSTRACT

Baltimore County's 48-inch PCCP Kenilworth Transmission Main, constructed in four phases between the 1970's and 1990's, serves 125,000 customers in the central part of the County. The main provided potable water, without incident, until it failed catastrophically in June 2003, adjacent to a local high school. Following an emergency repair, the same transmission line failed again nine months later, this time causing more severe damage to roads, underground infrastructure, and homes. After this second event, condition assessments and forensic analysis were conducted in late-2004, employing both visual and electromagnetic inspection technologies to evaluate the overall structural integrity of the pipeline, resulting in an emergency contract to replace four PCCP segments. Six years later in late-2010, in keeping with the County's policy to periodically inspect major transmission mains of questionable integrity, another re-inspection was performed, this time employing more advanced technologies as well as structural risk analysis and 3D finite element modeling. This led to the discovery of 33 PCCP sections that needed to be structurally rehabilitated or removed-and-replaced; decision needed to be made on the rehabilitation of the structurally deficient sections only, or the renewal of the entire length of pipeline in question.

After considering various repair options including carbon fiber reinforced composites (CFRP), removal-and-replacement with new PCCP sections, and structural sliplining with steel pipe or high density polyethylene (HDPE) pipe, the County decided to slipline the PCCP host pipe with spiral welded steel pipe. This paper not only discusses the history of the pipeline and its condition assessment and forensic analysis in detail, but also reviews the innovative decision processes involved with the selection of the appropriate rehabilitation method, material specification and drawing development. Discussion on the construction process of sliplining with steel pipe along with an evaluation of lessons learned is also provided.

INTRODUCTION

The Kenilworth Transmission Main is the primary feeder of potable water in northern Baltimore County's metropolitan water system. Along with a redundant 30-inch, the mains transport water into the Towson Fourth Zone and ultimately to five upper pressure zones. The transmission main is a very important piece of the Baltimore Water system and affects over 125,000 water consumers. The main was built in four phases between 1970 and 1991 and consists of 48,854 lf of 48-inch, 42-inch and 36-inch prestressed concrete cylinder pipe (PCCP), providing a conduit between the Towson Pumping Station and Mays Chapel Reservoir.

HISTORICAL BACKGROUND

The main provided water uneventfully for several years until June 2003 when the pipe failed adjacent to an area high school. A break on a key transmission main in the beginning of the high demand season was a major concern to County officials; therefore, an emergency procurement was placed in motion. The break was readily repaired by a local contractor working in the area and placed back in service in July, 2003. Nine months later, the main broke again approximately 4000 lf downstream. Unlike the first break, this failure caused significant damage to the road, underground infrastructure and adjacent homes. It was at this time that County engineers realized that there was a problem in this particular segment of the pipeline.

First Investigation: The County immediately hired a local consulting engineer, Patton Harris Rust and Associates (PHRA), to completely assess the condition of the pipeline. The preliminary investigative process revealed that the problematic segment was 7800 lf of PCCP (Embedded Cylinder SP-12), manufactured by the Interpace Corporation in 1977. Further investigation revealed that four design classes, A, B, C and D, were used for various site conditions and Class IV prestressing wire was utilized as its major structural component. The County was cautioned that this particular wire is sensitive to hydrogen embrittlement and is prone to premature failure.

The inspection was done in November, 2004 and employed two manual methods including an electromagnetic inspection and a more traditional visual and sounding inspection. The electromagnetic inspection, without calibration, included 394 pipe sections and revealed that 16% of these had wire breaks. In addition, 16 of these deficient sections exhibited more than 50 wire breaks. The visual and sounding inspection identified 4 sections showing longitudinal cracks and hollows in the core. One or both of these characteristics are indicators of structural distress. Based upon the results of both inspections and the correlation of the sounding and visual inspection with the electromagnetic findings, it was recommended that the 4 pipes with longitudinal cracks and hollows be removed and replaced prior to placing the main back in service. It is also noteworthy that the same 4 sections showed at least 50 wire breaks as reported by the electromagnetic analysis. Following the engineer’s recommendation, the County procured 4 PCCP repair assemblies and invited a select group of contractors to submit bids to replace the 4 pipe segments. American Infrastructure was selected as the low bidder and began replacement in May, 2005. During the installation, the contractor carefully removed the subject pipes to enable the County to embark on a forensic analysis.

Forensic Analysis Methodology: The forensic analysis was performed by Openaka Incorporated in a controlled environment. It began with the mortar coating being removed and exposing the prestresing wires. The pipe was examined in 1-ft intervals where wire breaks were counted, failure mode identified (whether it was indicative of a hydrogen embrittlement failure, corrosion, or other reasons) and mapped. Next, all wires were cut and the inner core removed to expose the steel cylinder. Areas of significant corrosion were identified and mapped as well. The results of the forensic analysis revealed a few interesting conclusions. The foremost purpose of the investigation proved that the results of the electromagnetic inspection were fairly accurate on 3 of the 4 pipes (the remaining pipe had several splices in the wire which created electromagnetic anomalies similar to broken wires). The other revelation was that 2 of the pipes removed were discovered to be Class A; however, the site conditions and consequently the lay schedule required a higher strength Class C design. The County concluded that the pipes that were investigated were in a state of failure due to corrosion, hydrogen embrittlement and substandard construction practices and the actions taken were certainly warranted and most likely avoided another catastrophic failure along this particularly problematic reach.

Test-Run of New Technology: In order to attain a rate of decay along this same reach, the County decided to employ the use of a hydrophone array for a trial period. Along with this technology, the first commercial installation of a fiber optic acoustic monitoring system was launched. The systems correlated very well and signaled 14 wire breaks over a 90-day period. The County thought this activity was acceptable and decided to suspend service of both the hydrophone array and fiber optic acoustic monitoring system after the trial.

Employing Advanced Condition Assessment Techniques: The entire Kenilworth Transmission Main operated without fault for 5 years. However, it is the County's policy to inspect major transmission mains of questionable integrity every 5 to 6 years. Therefore, in October 2010, the County's consulting engineer launched another inspection of the same 7800 lf reach that was inspected and subsequently repaired in 2004/2005. This inspection, however, would include structural risk analysis based on AWWA C304 (AWWA 2007a) and 3D finite element modeling.

The results of this inspection yielded a similar number in that 5 pipes were identified by the visual and sounding inspection to have longitudinal cracking and/or hollows and the electromagnetic inspection resulted in the identification of 40 pipes with wire breaks ranging from 5 to 75. The results were compared with that found in 2004; however, it was difficult to draw similarities between the two as the equipment, software, and experience have improved significantly over the 6-year period.

The design analysis with current standards, specifically AWWA C301 (AWWA 2007b), revealed that the pipe components used in the manufacture of the pipe in the seventies would not meet today's criteria and ultimately would fail prematurely. The engineer also looked at AWWA C304 (AWWA 2007a) Limit State criteria and given the existing static loading conditions and HS-20 live load, only Class A pipe met all the criteria. In addition, the finite element analysis found that micro cracking in the inner core would occur with all wires intact.

To enable the County to make a sound engineering decision regarding the replacement and/or rehabilitation of the pipes with broken wires, risk curves were created for each pipe design class at maximum cover. Analyzing the pipes with indicated wire breaks compared to the number of wire breaks that bring the pipe to its elastic limit, it was determined that 33 had reached this threshold. Given that this is the threshold that is generally accepted as a point to replace or structurally rehabilitate, the County had to make a decision to rehabilitate the 33 pipes or renew the entire reach.

CRITERIA FOR SOLUTION SELECTION

As the County embarked on the evaluation of an appropriate solution, the following issues were taken into consideration, shown below in order of importance:

1. Permanent solution for the entire length of the pipeline, i.e. a fully structural renewal that is not temporary
2. Overall cost of the technology
3. Minimum 100-year service life
4. Construction time
5. Minimizing hydraulic flow loss in host PCCP
6. Social costs (traffic and pedestrian disruption, resident and commercial inconvenience)

Pipeline renewal and repair options considered included carbon fiber reinforced polymers (CFRP), removal-and-replacement with new PCCP sections, and structural sliplining with either steel pipe or high density polyethylene (HDPE) pipe.

CONSTRUCTION METHODS AND MATERIAL EVALUATION

Carbon Fiber Composites: Baltimore County had some experience with the use of carbon fiber-reinforced polymer (CFRP) technology. This method had been used locally in scattered areas to repair short sections of deteriorated PCCP. In 2006, for example, Howard County used CFRP as an emergency temporary repair of several deficient sections of 36-inch diameter PCCP so that construction on a planned railroad could be expedited (Donaldson et al. 2008). However for the Kenilworth PCCP failures, it was deemed necessary to ensure that the entire pipeline be permanently rehabilitated to eliminate the risk of further failures and resulting safety concerns, costs and disruptions to the public. Continued deterioration of PCCP sections following partial repairs within a system is a common phenomenon throughout the country, and therefore needed to be eliminated on the Kenilworth line. When temporary and partial repairs with CFRP were being considered, the rehabilitation of 33 pieces, or 264-ft, of the most distressed sections of the pipeline was valued at $2.5 million. And there were also no guarantees that the remaining 7,500 sections of PCCP would not further deteriorate after the most deficient 33 sections were repaired with CFRP.

Remove-and-Replace: As is the case when considering permanent repair solutions to long lengths of PCCP lines, Baltimore County evaluated the remove-and-replace option for the failing PCCP. The area where the pipeline is located is in a congested suburban locale with shopping centers and a large regional mall close by. The pipeline alignment is in the shoulder or under the pavement of very busy roadways. Most of the area above the road had over-head electric lines. The remove-and-replace option was abandoned because of associated traffic disruption, commercial disturbance with loss of business, environmental and social impacts, construction time, existing utilities, and budget constraints.

Structural Sliplining with HDPE: The County also considered sliplining the PCCP with High Density Polyethylene pipe (HDPE). After review, it was not a viable alternative due to the large reduction of inside diameter (ID) of the host pipe and its hydraulic capacity. Evaluation showed 42-inch DR 11 HDPE 4710 material had an ID of 33.905-inch compared to the 40-inch minimum ID for steel pipe manufactured to AWWA C200 (2005). In addition, assembled lengths of butt-fused HDPE could not be strung out prior to insertion due to traffic and pedestrian disruption and staging area constraints. Specialized fusion machines and operators, along with the time necessary for assembling each 42-inch diameter HDPE pipe joint were not cost-effective.

Structural Sliplining with Steel Pipe: The final option evaluated was the sliplining of the PCCP with steel cylinders. Based on the advantages this option provided, such as minimal loss of flow whereby the steel slipliner pipe would have a minimum ID of 40-inch, an engineered lining system with zero-leakage welded joints, and a fully-structural, permanent renewal of the host pipe, the selected approach was to slipline the existing PCCP with an AWWA C200 Spirally Welded Steel Pipe (WSP). Using this technology, the County was able to obtain all six of the pre-defined requirements: 1) a fully structural permanent solution that would be stand-alone should the host PCCP deteriorate fully over time, 2) more cost effective compared to the remove-and-replace option and CFRP repair, 3) protection from corrosion using effective lining and coating systems, as well as cathodic protection, with the ability to continuously monitor the condition of the line against corrosion using test stations, leading to a service life of 100 years minimum, 4) a considerably lower construction time compared to removing-and-replacing the entire pipeline with new pipe, 5) minimal loss of internal flow area in the host pipe when compared to sliplining with HDPE, and 6) minimized traffic disruption, inconvenience to the public and businesses, and other social costs since sliplining is a semi-trenchless construction method and provides substantial benefits over open-cut processes such as remove-and-replace.

PROJECT DESIGN

The County along with the assistance of the WSP manufacturer, Northwest Pipe Company (manufacturer) worked together to develop a specification for sliplining. Staging areas, entry and exit pits, strength of the WSP to withstand jacking forces, geotechnical and sub-surface conditions, and the condition of the host pipe were all given appropriate consideration. This process moved quickly beginning in September 2010 and ending in November 2010. At that point the WSP slipline package was ready for advertisement.

The project involved 7,800 lf of 40-inch ID WSP with a 41 ¾-inch OD designed per the AWWA M11 Steel Water Pipe Design Manual (AWWA 2004), and the requirements of the AWWA C200 standard, sliplined into the existing 48-inch diameter host PCCP line. The working pressure of the pipeline was 120 psi, with a test pressure of 180 psi. Figure 1 shows the project alignment.

The WSP was designed for internal pressures, external earth loads and as appropriate, external hydrostatic pressures from ground water, all per AWWA M11. Grouting the annular space between the carrier and casing is normal protocol for sliplining to provide uniform support to the carrier pipe and was so specified on this project. Being their first slipline project of PCCP, Baltimore County was concerned with possible excessive grouting pressures from improper grouting procedures leading to buckling of the internal liner pipe. This led the County to be conservative and specify a wall thickness of 3/8-inch which is approximately twice the thickness indicated by the M11 design procedure for internal pressures and external earth loads. The WSP was therefore capable of handling twice the required internal pressure of the host pipe. Corrosion protection design specified the outside of the slipliner WSP to be bare steel with the annular space between the casing and the carrier completely filled with a cementitious, low weight grout. Also, an anti-corrosion inhibitor was specified in the mix to assist in protecting the pipe against corrosion. For corrosion protection on the WSP in the open-cut sections, a bonded 80-mil dielectric tape coating system was specified that exceeded the requirements of AWWA C214 (AWWA 2007c). Cement Mortar Lining (CML) was specified with a ½-inch thickness for the inside of all pipes per AWWA C205 (AWWA 2007d) standard.

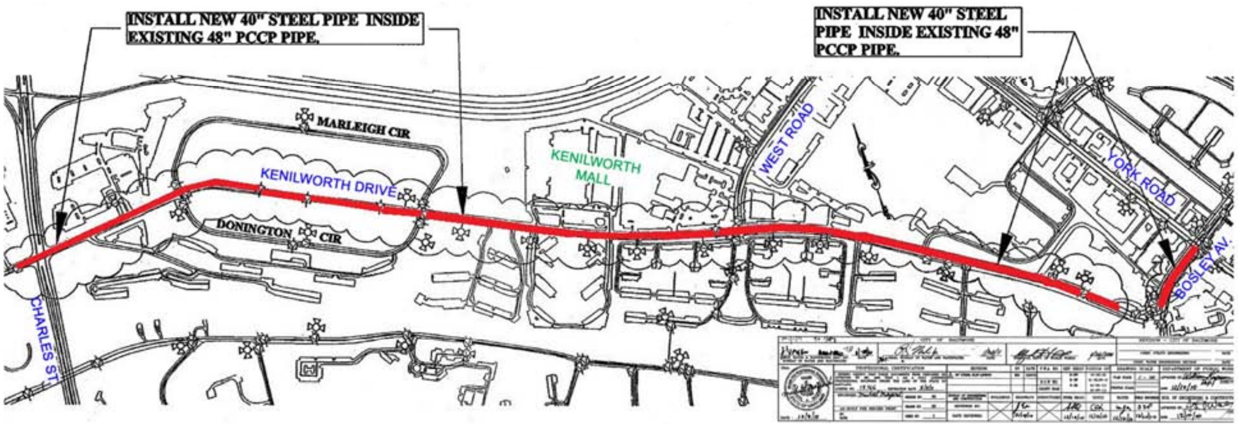


Figure 1: Project Alignment, Along Kenilworth Drive

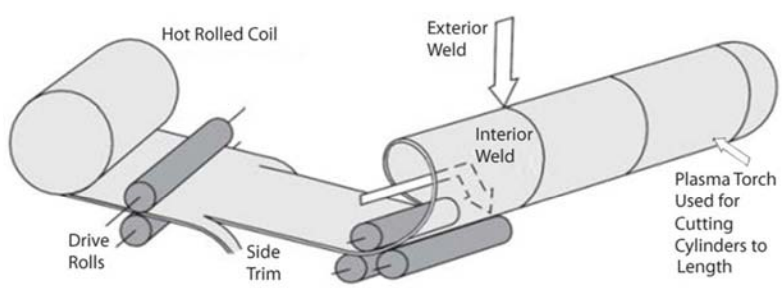
The primary bid specification package allowed for the contractor to determine pipe lengths to be inserted into the host PCCP. The standard bell by spigot with interior single lap weld was specified as the standard joint. As the liner pipe was inserted bell-over-spigot in a cartridge-style with the joints not initially welded, the pipe sections were able to rotate on their own axis as they were jacked in and traveled down the host pipe. This greatly assisted in negotiating bends and offsets. Once the pipe string was inserted into place and final fit up of each joint was made, each joint was internally lap-welded. The County provided the original layout drawings for contractor evaluation for bidding. The original PCCP line showed a tight radius. The curve radii varied from 595 ft to as high as 3,000 ft. It would be the responsibility of the contractor to determine pipe lengths for the pushing or pulling of the pipe into place and to determine as-built condition of the existing PCCP. As feared, the lay drawings did not always match the as-built conditions, so field survey was appropriate.

PROJECT BID & AWARD AND PIPE MANUFACTURE

On January 13, 2011 the project was bid and within two weeks it was awarded to American Infrastructure (the contractor) of Fallston, MD, with a bid-price of $4,965,000. The contractor and pipe manufacturer worked together during the pre-installation phase to determine which sections would be sliplined, and the appropriate joint lengths. For example, the contractor had the option to either open-cut or slipline a section on Bosley Ave. Even though they had initially decided to open-cut in that roadway, they later decided to slipline it due to the good preceding experience with sliplining the longer Kenilworth Drive sections.

The Contractor elected to use 20-ft pipe sections as a standard length and used 10-ft sections on bends with tighter radii. The 10-ft sections, each with its own bell and spigot, allowed for the shorter pipe to act as a “slinky” to articulate the bends and curves. The rule that governs the “pull,” or angular deflection at a weld joint, is three times the pipe wall thickness, or 1-inch minimum, whichever is greater. Northwest Pipe developed a line lay-out based on the original drawings, utilizing 20-ft and 10-ft lengths where necessary to accommodate bends and offsets. After the contractor and the County reviewed and approved these drawings, the pipe was manufactured to the Project Specifications and applicable AWWA Standards.

Pipe Manufacture: WSP is manufactured from steel coils formed helically into cylinders, Figure 2a. The pipe seams are double submerged arc welded as they are being formed. This process allows the pipe to be manufactured to any diameter required by the user, allowing the flexibility and ability to have a fully engineered slipliner pipe as large as can be fitted into the host pipe without having to sacrifice hydraulic capacity due to "standard" pipe diameters, as is the case with other pipe materials such as HDPE, PVC and DIP. Steel pipes manufactured to AWWA C200 do not conform to a preset diameter-regimen such as IPS or CIOD by default. On the steel mill, cylinders are cut to their desired lengths using a plasma torch, Figure 2b. Each length of pipe produced is hydrostatically shop-tested to 75% of the specified minimum yield strength of the steel. In this case, the hydrostatic test pressure for the 41.75-inch OD pipe with a 0.375-inch wall was 566 psi. Unlike DIP, PVC, and other pipe materials which are shop hydro-tested for only 5 seconds each, hydrotesting of C200-compliant WSP requires that the pressures be held for a minimum of 30 seconds, or as long as needed to visually inspect all the spiral weld seams.



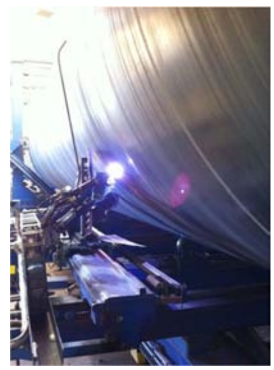


Figure 2a, b: Spiral-Welded Steel Pipe (AWWA 2004), Plasma Torch for Cutting Cylinders to Appropriate Lengths

Lap weld joints are provided by precision expanding one end of a section of pipe, Figure 3a, to form the bell end, Figure 3b. The spigot end is simply the cut end of the pipe.

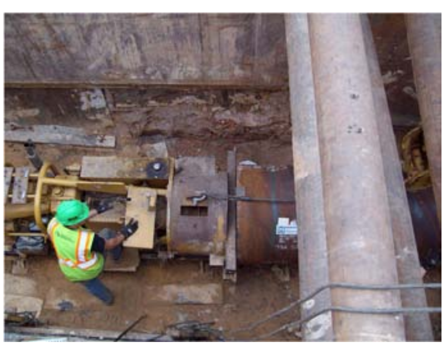
Figure 3a, b: Hydraulic Bell Expander, Completed Bell

INSTALLATION

The Contractor used casing spacers to center the steel pipe in the host PCCP. The casing spacers were made of hard polymer plastic, Figure 4a. Three casing spacers were used for each 20-ft section, Figure 4b, and two spacers on 10-ft sections. This system allowed the WSP to easily transverse through the host pipe, and also articulating at offsets, angles and bends. These spacers provided a uniform space around the liner pipe in preparation for the grouting process.


Figures 4a, b: Casing Spacers, 3 Casing Spacers per 20-ft Steel Cylinders

The contractor constructed ten pits, including tie-in locations. Each area was sufficiently long to accommodate the pipe lengths and the jacking equipment. Sliplining lengths varied from 600-ft to 1000-ft. Pit locations were selected based on bends from the drawing details, pushing distance and connection areas. The contractor excavated the area and pulled out the original section of host pipe in this immediate area, but left the areas adjacent to the openings with the bottom of the PCCP in place. This base gave the steel pipe a track to place the slipline pipe, prior to pushing in place. All areas of the open pits were dewatered during this operation. Instead of using a rail system as would typically be the case, the contractor used a jacking machine with a connection sled to push the pipe into place, Figure 5a. Pipe was located with the corresponding mark number and loaded onto the sled, sequentially in cartridge fashion. Mark numbers ensured that the correct pipe section was being inserted so that it would find its correct location in the slipline operation. The contractor's jacking equipment was limited to performing 800-ft long jacking operations. For several of the 1000-ft sections, an excavator was utilized to facilitate movement of the steel liner pipe downstream while the jacking machine continued to push on the upstream liner sections, enabling the completion of the 1000-ft runs of sliplining.




Figures 5a, b: Jacking Machine, Cartridge-Method Insertion

Reconnections: The insertion pits allowed the contractor to make new connections of the new steel pipe to existing infrastructure such as valves, meters and other appurtenances. Mechanical couplings were used to make connections to new and existing pipe. After the pipe section train was completed between adjacent pits, pipe spools were set in place to make final connections, using butt straps. All buried pipe not coated at the plant was either hand tape coated per AWWA C209 (AWWA 2000) or a heat shrink sleeve was applied per AWWA C216 (AWWA 2007e). This ensured that the entire area was hermitically sealed from the underground environment protecting the steel pipe from any type of underground corrosion.

Welding: After each pit-to-pit train was completed, welders went into the pipe to internally lap weld each piece of pipe. Pipe welding was completed per AWWA C206 (AWWA 2003) and AWS B2.1 (AWS 2005) — standards for field welding procedures and welding qualifications, respectively. The contractor utilized OSHA approved confined space entry equipment and apparatus, Figure 6. After welding completion, the specifications required that each weld was third party tested with a magnetic particle examination per the ASTM E709 (ASTM 2001) standard. After each weld was tested and approved, the Contractor used a cement epoxy compound to grout the internal joint to provide a continuous cement mortar lining of the pipeline.

Figure 6: OSHA Approved Ventilation Equipment w/ Corrugated HDPE Ducts

Grout: After review of the original grout specification by the contractor, it was determined that a more efficient light weight cellular foam grout mix could be utilized with the specified anti-corrosion product as part of the grout design; this was accepted by the County and used on the project. The 28-day compressive strength of the grout per ASTM C495/C796 was over 100 psi.

Procedure for Grouting: The grouting process was completed from pit to pit. Water in the casing was first removed. Watertight bulkheads were placed on both ends of the pipe so that the annulus was blocked off. Air relief valves were provided at both ends of the line. The WSP was filled with water. The grout was then poured in from a filler pipe on the downstream end and allowed to flow through gravity from one end of the pipe to the other. A splashboard, for gravity feed, was used to pour the grout at the top of the downstream side. When the grout ran out of the upstream relief valve, the grouting was completed. The grout pressure did not exceed 5psi and resulted in100% of the annulus being filled. The specification required that there be multiple grout ports in each pipe to inspect the annulus or to fill the annulus up from the inside. With these state of the art "flowable" grout mixes, the use of grout ports was unnecessary.

Cathodic Protection: In accordance with the project cathodic protection plan, test stations were installed along the pipeline route at approximately 800-1000-ft intervals, at each insertion and receiving pit. The 20-ft long receiving pits contained four 20-lb magnesium anodes and the 40-ft long jacking pits contained eight 20-lb magnesium anodes. The test stations allow for future monitoring of the WSP performance.

Field Hydro-testing: After all the WSP liner had been installed in the host pipe and reconnection to existing infrastructure completed, a hydro-test was performed at 180 psi. With the welding of the grout ports, no leaks were found.

CONCLUSION

After considering all the possible alternatives to replace or rehabilitate the failing 48-inch PCCP Kenilworth Transmission Main, the best alternative was to slipline the deteriorated pipe with a welded steel pipe slipliner system. The WSP was designed to meet all operating criteria. The pipe, cement mortar lining and tape coatings were manufactured to applicable AWWA standards. The WSP liner provided a permanent, fully structural system designed to provide a 100 year service life. The use of single lap welded bell-by-spigot restrained joints allowed the pipe flexibility in insertion into the host pipe and to be welded on the interior after insertion. The use of 20-ft or 10-ft joints allowed the contractor to navigate tight bends and curves without the need for fittings. The new pipeline has a continuous cement mortar lining, an anti-corrosion cement coating in the slipline areas and a bonded dielectric coating in the open pit areas, all supplemented with cathodic protection to assure longest service life. Baltimore County is very pleased with their first major slipline of failed PCCP with steel water pipe.

REFERENCES

ASTM (2001). "Standard Guide for Magnetic Particle Testing," *E709-01*, ASTM International, West Conshohocken, PA.

AWS (2005). "Specification for Welding Procedure and Performance Qualification," *AWS B2.1:2005*, American Welding Society, Miami, FL.

AWWA (2000). "Cold-Applied Tape Coatings for the Exterior or Special Sections, Connections, and Fittings for Steel Water Pipelines," *AWWA-C209-00*, American Water Works Association, Denver, CO.

AWWA (2003). "Field Welding of Steel Water Pipe," *AWWA C206-03*, American Water Works Association, Denver, CO.

AWWA (2004). "Steel Water Pipe: A Guide for Design and Installation (M11)," *AWWA-M11*, American Water Works Association, Denver, CO.

AWWA (2005). "Steel Water Pipe-6 In. (150mm) and Larger," *AWWA C200-12*, American Water Works Association, Denver, CO.

AWWA (2007a). "Design of Prestressed-Concrete Cylinder Pipe," *AWWA C304-07*, American Water Works Association, Denver, CO.

AWWA (2007b). "Prestressed Concrete Pressure Pipe, Steel-Cylinder Type," *AWWA C301-07*, American Water Works Association, Denver, CO.

AWWA (2007c). “Tape Coating Systems for the Exterior of Steel Water Pipelines,” *AWWA C214-07*, American Water Works Association, Denver, CO.

AWWA (2007d). “Cement-Mortar Protective Lining and Coating for Steel Water Pipe — 4 In. (100mm) and Larger — Shop Applied,” *AWWA C205-07*, American Water Works Association, Denver, CO.

AWWA (2007e). “Heat-Shrinkable Cross-Linked Polyolefin Coatings for the Exterior of Special Sections, Connections, and Fittings for Steel Water Pipelines,” *AWWA C216-07*, American Water Works Association, Denver, CO.

Donaldson, F., Persinger, W.C., Morrison, R. S., Lieu, D., Jarvis, H., and W. Parrish (2008). "Quality Control of Carbon Fiber Composite System Repairs of PCCP from the Inspector’s Viewpoint," *ASCE Pipelines 2008: Pipeline Asset Management - Maximizing Performance of Our Pipeline Infrastructure*, S. Gokhale and S. Rahman, eds., American Society of Civil Engineers, Reston, VA.

Donaldson, F. and G. Lake (2005 amended 2008) “48-inch Water Main Inspection, Master Agreement 205, Task 2”

Donaldson, F. and G. Lake (2011) “Inspection and Condition Assessment of the 48-Inch Kenilworth Drive Water Transmission Main, Master Agreement 205, Task 11”