Rehabilitation of Large Diameter PCCP: Relining and Sliplining with Steel Pipe

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ABSTRACT

Failures of Prestressed Concrete Cylinder Pipe (PCCP) throughout North American municipal water transmission systems since the 1970's has led to the development of a myriad of rehabilitation technologies. Besides removing and replacing full sections of distressed pipe with new pipe, the most widely used method of rehabilitation of PCCP is the structurally independent, Type IV relining of the host pipe with steel cylinders. Referred to as Steel Cylinder Relining or Sliplining, both of these semi-trenchless technologies allow a fully structural renewal of long lengths of PCCP in an economical and expeditious manner. The differences between Relining and Sliplining are discussed from the standpoint of manufacture, flow capacities, design, planning, installation and corrosion protection. The paper also provides a description and comparison of other rehab technologies.

INTRODUCTION

The catastrophic failure of Prestressed Concrete Cylinder Pipe (PCCP), manufactured to AWWA C301 standards, presents a significant challenge to Owners of large diameter water transmission systems in North America. Similar problems have surfaced in recent years in nuclear, coal-fired and gas-fired power generation plants that installed PCCP lines to transport water between cooling towers and condenser heat exchangers during construction. This paper focuses on the municipal water transmission segment, defines and quantifies the scope of the problem with large diameter PCCP transmission pipelines, and discusses various rehabilitation technologies that have evolved to sustain the longevity of problematic PCCP systems. The structurally independent, Class IV Relining and Sliplining solution provided by the use of steel cylinders is the primary focus; discussion on the cylinder manufacture process, planning, and installation is presented. Information is also provided on the PCCP rehabilitation programs of the San Diego County Water Authority (SDCWA), Metropolitan Water District of Southern California (MWDSC) and the City of Phoenix Water System.

Large Diameter Water Transmission Mains: Over the last sixty years, the large diameter water transmission mains market has primarily been served by steel-cylinder-type concrete pressure pipes (AWWA C300, 301, C303), spirally welded steel pipes (AWWA C200), and to a lesser extent, by ductile iron pipes (AWWA C150, up to 64-

inch diameters). While steel pipes have been in use for more than 150 years, with the first recorded installation taking place in 1858, composite concrete pressure pipes that make use of the tensile strength (post-tensioned or prestressed) of steel wire reinforcements, a steel cylinder, and the compressive strength of concrete, first appeared on the market out of necessity during WWII due to steel shortages. Use of non-cylinder reinforced concrete pipes (AWWA C302) began in the 1920's and was widely accepted by the 1930's. The first cylinder-type concrete pressure pipe, specifically AWWA 301 prestressed concrete cylinder pipe, was installed in 1942 (AWWA 2007). At the height of its popularity in the 1970's, there were six major manufacturers of PCCP in the US, with at least twenty-two plants scattered throughout the country; there were at least two large manufacturers in Canada also. Today there are three PCCP manufactures in the US, with a total of six plants. For large diameter water transmission applications, steel pipe is most widely used now, with two of the three PCCP manufacturers in the US also making steel pipe. Four major steel pipe manufacturers with eleven plants located around the US are the main suppliers of steel water transmission pipe.

AwwaRF Study on PCCP: Most post-WWII large-diameter pipeline infrastructure needs were met by PCCP. More than 19,000 miles of PCCP was manufactured and installed between 1940 and 2006 (Romer and Bell 2008). Failures of PCCP first began in 1955, and became more noticeable in the early 1980's (Goldstein 2009). Romer and Bell (2008) provide a database of 592 independent entries of three different types of failures --- catastrophic ruptures, failures discerned by inspection, and failure through loss of service --- of PCCP, gathered from Owner utilities in 35 different states and the District of Columbia. Highlights of the report include:

- Within 50 years of installation, one rupture and 66 other failures occurred for every 50-miles of PCCP
- A significant increased rate of failure occurred on pipe manufactured between 1971 and 1979, attributed to type IV wire that was used for prestressing during that period by a particular pipe manufacturer (manufacture process of wire induced longitudinal cracks, and made them particularly susceptible to hydrogen embrittlement)
- The report lists more than twenty other reasons attributed to PCCP failures besides those directly related to the type IV prestressing wire
- 50% of the catastrophic failures recorded in the study involved pipe manufactured during the 1971 to 1979 time frame; 39% of these were attributed to a single manufacturer. The remaining 11% had different or unknown manufacturers
- The remaining 50% of catastrophic failures occurred in pipes manufactured from 1940's through 1971, and from 1979 through 2006, respectively

Since the publication of the Study, failures have continued to occur and as a consequence, interest in PCCP assessment and rehabilitation continues.

Quantifying the PCCP Problem: According to the condition assessment industry, after fifteen years of surveying various PCCP systems around the country, they have reached the conclusion that four percent (4%) of PCCP lines have *high levels of distress* (Stadnyckyj 2010). With 19,000-miles of PCCP having been installed between 1940 and 2006 (Romer and Bell 2008), it can be surmised that there could be more than 600-miles of highly distressed PCCP lines currently in service nationwide.

REHABILITATION TECHNOLOGIES

In the past 20 years, there has been five different solutions employed to sustain the longevity of PCCP systems: remove and replace entire sections of pipe with new pipe, Relining the host pipe with collapsible steel cylinders, Sliplining the host pipe with full sections of steel pipe, compensating for the loss in strength of pipe sections due to damaged prestressing wires with an externally applied post-tension tendon repair method, and the use of carbon fiber composites (CFRP) to internally reline sections of PCCP that have been identified as distressed or deficient. A sixth method occasionally used, and not discussed herein, is concrete encasement of distressed PCCP sections.

Remove-and-Replace: This is an option that is usually considered when there are vast sections of a pipeline in need of urgent repair, or when a line is located in a rural area with no right of way restrictions. Economically, this may not be the best option; the cost of removing existing sections of pipe and replacing them with new pipe presents the same challenges as new construction, especially when performed in urban environments. Traffic management and other associated social costs can make it unattractive. Instances where removal-and-replacement has been performed in recent years, such as on the 84-inch Lake Tawakoni PCCP line of the Dallas Water Utilities, corrosion damage on the host PCCP was extensive; in this case, there were 465 sections of deficient PCCP (Hooten and Cooper 2005). The pipeline alignment of Lake Tawakoni was also rural and presented minimal traffic disruption issues. The replacement pipe material was PCCP. In the western United States, whenever removal-and-replacement is the selected option, the replacement pipe is usually spirally welded steel pipe, with appropriate corrosion protection (SDCWA 2012a and 2012b).

Steel Cylinder Relining: Relining consists of insertion of collapsed steel cylinders into the host pipe, re-rounding in into place and performing the necessary welding, followed by cement-grouting of the annular space between the liner and host pipe. Cement mortar lining is then applied to the inside of the cylinder. Figure 1a through 1d show the key steps involved in Relining.

Figure 1a, b, c, d: Collapsed Reliner Cylinder, Insertion of Reliner into Host PCCP, Expansion and Welding of Reliner, In-field Lining Application

The Relining of PCCP with steel cylinders provides a fully structural or *structurally independent* rehabilitation solution with a long-term (100 years) internal burst strength, when independently tested from the host pipe, equal to or greater than the Maximum Allowable Operating Pressure (MAOP) of the host pipe. The lining system is also capable of surviving any dynamic loading or other short-term effects associated with a complete failure of the host PCCP, usually due to deteriorating soil conditions and further corrosion of various components of the deficient composite host pipe. These two capabilities place the Relining with steel cylinder option into the Class IV Linings category as described in AWWA M28 (2001).

Some of the largest water agencies around the country have adopted steel pipe Relining as a permanent, long-term solution to their problematic PCCP systems, and are systematically rehabilitating all of their PCCP lines with steel cylinders. Relining is considered "semi-trenchless" because entry and exit portals need to be made at the two ends of the pipeline being renewed. The method is ideal for structural renewal of long lengths of pipelines and is less suited for the rehab of single, isolated sections of PCCP in urban areas. Smith and Bruny (2004) describe a sizeable project where steel cylinder Relining was employed to renew vast sections of PCCP of the San Diego County Water Authority. Ambroziak et al. (2010) describe the nation's largest PCCP water main rehabilitation by Relining with steel cylinders at the City of Phoenix.

Steel Cylinder Sliplining: Sliplining involves the insertion of full sections of steel pipe into the host pipe, Figure 2a, connecting the adjoining pipe sections, and then filling the annular space with cement-grout. A cement mortar lining is then applied to the cylinder. This method also meets the AWWA M28 classification of structurally independent Class IV Linings, and is suited for the structural renewal of long lengths of a PCCP line. Due to the conventional way in which the cylinders for Sliplining are made, manufacture is faster and less labor intensive than Reliner cylinders, and therefore, usually lower cost. Installation productivity is also faster with Sliplining than Relining, discussed further in the paper.

Ambroziak et al. (2009) describe the Sliplining of 8,300-ft of 60-inch PCCP on the Superior Waterline at the City of Phoenix, Figure 2a. Bass et al. (2011) report on the Sliplining of a 48-inch PCCP transmission main at Halifax Water with a unique gasket-joint design, Figure 2b.

Figure 2a, b: Sliplining 60-inch PCCP in Phoenix, Sliplining 48-inch PCCP in Halifax, Nova Scotia (Bass 2011)

Post-Tension Tendon Repair: More often used in repairing above-ground circular structures such as tanks and silos, there are limited known uses of this technology in PCCP systems around the US. The process involves compensating for the strength lost in the host PCCP due to corroded prestressing wires with post-tensioned steel tendons placed externally around the pipe, Figure 3a. The distressed section of PCCP must be fully dug out, following which post-tensioned steel cables are wrapped around the outside of the pipe, then coated with a pneumatically-applied layer of shotcrete.

Figure 3a, b: Post-tension Tendon Repair in Libya (Elnakhat 2006), CFRP Application (Rahman 2008)

This technology is not suited to the repair of long lengths of PCCP and whenever employed, is rarely used to strengthen more than one to five sections of the host pipe at a time. Ojdrovic and LaBonte (2008) report on four sections of distressed PCCP in a power generation plant, one of which was repaired using post-tensioning, while a different technology was employed to repair the remaining three sections. The City of Tucson has used this repair option on a few sections of 66-inch diameter PCCP (Larsen 2009). The only known large-scale application of this process has been on the Great Man Made River pipeline in Libya (Elnakhat 2006). For long-term corrosion protection, the steel hoop-tendons rely on corrosion-inhibitors and are encapsulated in polypropylene sheathing, and are not known to be cathodically protected. An advantage of this repair method is that the host pipe does not have to be placed out of service or dewatered, even though most utilities that have used this technology usually put their system temporarily out of service during repair.

Carbon Fiber Reinforced Polymers (CFRP): First applied inside a PCCP cooling line at a nuclear power plant in Arizona in the late 1990's, carbon fiber composite repair has been used in several municipalities around the US since that time. However, many of these municipalities use CFRP as a temporary repair option until a more permanent solution such as steel cylinder Relining or Sliplining is applied. Work with CFRP is specialized and requires skilled labor (Rahman 2008, Arnold et al. 2008). Layers of epoxy-wetted CFRP are applied manually in layers, Figure 3b; the orientation of the fiber provides reinforcement to the host PCCP in the corresponding direction, while the number of layers determines the strength of the lining system.

The technology is still considered relatively new, with the first AWWA standard for CFRP repair of PCCP currently being developed. The greatest advantage of CFRP rehab is that it is a trenchless process, with minimal disruption to above-ground traffic. Repair can be designed to be fully or semi-structural. Fully structural repair is typically very expensive compared to other technologies. In general, this technology is ideal for performing work on a limited number of isolated sections instead of long sections of an existing pipeline. Man-way access into the host pipe is essential and the pipe has to be placed out of service while repair is performed. The cure time of the epoxy-wetted carbon fiber composite system can take 24 hours or longer, depending on the number of layers being applied. Table 1 provides a comparison of the five different options discussed.

Table 1: Comparison of Rehabilitation Technologies

Repair Method	Traffic Disruption	Environmental / Social Impact	Construction Time
Reline w/ Steel Pipe	Moderate	Moderate	Moderate
Slipline w/ Steel Pipe	Moderate	Moderate	Moderate
Remove and Replace	High	High	High
Post-tension Tendon Repair	High	High	High
Carbon Fiber Composites (CFRP)	Low	Low	Moderate

Cost comparison of the Type IV reline methods vary widely based on the amount of repair needed, accessibility, diameter of the host pipe, internal pressure requirements, urgency of repair and market conditions, to name a few variables. In general, steel cylinder-based repair options are no more expensive than other methods, and for large projects, are the lowest cost option.

COMPARISON OF RELINING & SLIPLINING

Manufacture: The manufacture of collapsible cylinders used in Relining is a specialized process and involves many additional steps not typical in the manufacture of rolled-and-welded or spirally welded steel cylinders. It is labor intensive, and therefore, more costly to produce. Sliplining cylinders are made using conventional equipment and machine welds. Willaims et al. (2006) and Smith and Bruny (2004) provide a description of the complexity of Reliner cylinder manufacture.

The fabrication of Sliplining cylinders is identical to the standard manufacture of AWWA C200 (2005) steel water pipe, as outlined in the standard itself as well as in the AWWA M11 (2004) design manual for steel pipe design. Polly (2012) provides a description of the manufacture process.

Finished Internal Diameters: Being able to traverse the host pipe with sections of steel cylinder when Sliplining is a key concern. To accommodate this, the OD of Slipliner cylinders are smaller than the OD of Reliner cylinders (after the collapsed Reliner cylinders have been expanded and welded). Lengths of Slipliner cylinders are also sometimes made shorter than Reliner cylinders to allow more deflection points if needed to match the alignment of the host pipe. For a 60-inch diameter host pipe, loss of internal capacity may be 6 to 8-inches with Sliplining, and 3 to 4-inches with Relining. In both cases, the cylinder thickness can be designed to compensate for reduced flow areas or upgrades of internal pressure due to increased demands in the system. Hence both systems not only rehabilitate the PCCP, but can also provide a pressure upgrade of the system.

Design: To determine the appropriate wall thickness for hoop stress, of both Reliner and Slipliner cylinders, the AWWA M11 (2004) can be utilized. It should be verified that the selected wall thickness is able to withstand the grouting pressure. If the pipe is to withstand any jacking forces, appropriate calculations should be done to check the adequacy of the cylinder against these longitudinal forces.

Planning: Selection of appropriate locations for insertion portals, Figures 4a, 4b and 4c, is a critical part of the planning process. They are typically placed at significant bends in the pipeline, or where surface conditions will allow. Above-ground and sub-surface conditions, existing utilities in the vicinity of the project, and depth of bury of the host pipe need to be known. Conditions both inside the host pipe and on the ground surface need to be used to determine the location of portals and the distance that can exist between portals. As already mentioned, particularly during Sliplining projects, it is important to ensure the maneuverability of the Slipliner cylinders inside the host pipe; existing collapses or excessive vertical deflections inside the host pipe should be taken into account and appropriately addressed.

Figure 4a, b, c: Insertion Portal for 96-in Dia. PCCP at SDCWA, 60-in Dia. PCCP Portal in Highly Urban Section of City of Phoenix, Insertion Portal for 48-inch PCCP at a Bend in Halifax, Nova Scotia

Installation: Cylinders are transported into the host pipe with motorized machinery, winches or rams, depending on the layout and type of steel liner. The fit-up of Reliner cylinders is more time consuming than Slipliner cylinders; longitudinal welds must be applied after the liners are released and re-rounded. Each section of re-rounded liner must then be circumferentially welded and permanently joined on to the adjoining section. Slipliner cylinders need only be circumferentially lap welded to the adjoining cylinder, reducing labor requirements. Non-destructive tests (NDTs) per AWWA are used to check welding quality. Slipliner cylinders typically come from the factory with cement mortar lining. Sliplining cylinder installation is therefore more rapid than Relining, leading typically to higher productivity. Using a 60-inch host pipe example again, it would be possible to install 25 to 35 cylinders per day when Sliplining versus 10 to 20 cylinders per day when Relining.

Lining and Coating: The exterior of both Reliner and Slipliner cylinders is typically bare as the annular space between the liner and host pipe are grouted. Properly applied, the grout provides structural support and also prevents external corrosion. As already mentioned, Slipliner cylinders are already shop-lined with cement mortar prior to installation into the host pipe. This is not an option for Reliner cylinders, which must be cement-mortar lined in the field following re-rounding and installation into the host pipe. For very large diameter Slipliner cylinders, typically greater than the 96-inch to 120-inch diameter range, in-field application of cement-mortar lining is the norm, Figure 1d. Table 2 summarizes the key differences between Relining and Sliplining.

Table 2: Differences between Relining and Sliplining

	Relining	Sliplining
Manufacture	Specialized process	Same as AWWA C200 steel water pipe
Finished Internal Diameter	Minimal flow loss in host pipe (3-in to 4-in for 60-inch Diameter Pipe)	Moderate flow loss in host pipe (6-in to 8-in for 60-in Diameter Pipe)
Design	Wall thickness for Hoop Stress as calculated in AWWA M11. Verify wall thickness adequacy for grouting	Wall thickness for Hoop Stress as calculated in AWWA M11.Verify wall thickness adequacy for grouting and jacking forces (if applicable)
Installation	Welding of longitudinal seams and connecting joints	Welding of only connecting joints
Corrosion Control	External corrosion control by grouting, internal corrosion control by in-field cement-mortar lining	External corrosion control by grouting, internal corrosion control by shop-applied cement-mortar, or in-field cement-mortar lining for larger diameter cylinders
Cost	More costly than Sliplining due to specialized cylinder manufacture and added in-field welding needs	Less costly than Relining due to conventional steel cylinder manufacture and no in-field longitudinal seam welding

OWNER MANAGEMENT OF PCCP SYSTEMS

The municipal water community found itself unprepared to deal with the PCCP issues. In 1991, the Chief of Engineering at Denver Water initiated the first gathering of Owners to assess the catastrophic failures and owners experiences, resulting in the founding of the PCCP Users Group (ASCE 2011). More than twenty years later, various PCCP owners around the country have instituted condition assessment programs and are allotting substantial annual funding for both emergency repairs as well as the systematic rehabilitation of deficient portions of their water transmission systems. The market for permanent Type IV reline products has grown significantly. The initiatives of 3 large owners are discussed here.

San Diego County Water Authority (SDCWA): The Water Authority is a wholesale water supplier to 24 agencies in the San Diego, CA area, serving a population of more than 3.5 million. There are 5 major pipelines, with a total of 300 miles of pipe in the system. Approximately 85 miles of this is large diameter PCCP. Due to catastrophic failures of several sections, the Water Authority has embarked on a multi-year condition assessment program to identify at-risk pipes and prioritize repair. There is also a 30-year program to ultimately Reline the entire PCCP portion of their system with steel cylinder. Depending on the availability of funding and the general condition of a section, major rehabilitation initiatives by Relining are undertaken every four to five years that gets the Water Authority closer to its goal of Relining all 85 miles of PCCP. Any PCCP pipes that have been removed out of the ground have been replaced with steel pipe. Technologies other than Sliplining are occasionally specified for temporary, emergency repairs. To date, the Agency has Relined approximately one third of their PCCP system with collapsible steel cylinders. The most recent Relining project will rehabilitate 2,400-ft of Pipeline 3, 69-inch diameter, and 16,600-ft of Pipeline 4, diameter 72-inch, from SR52 to Lake Murray. The project will also replace 60-ft of PCCP with steel pipe (SDCWA 2012). In 2004, Pipelines 3 and 4 also underwent Relining that included 16,285-ft of 96-

inch, 2,330-ft of 72-inch, 10,600-ft of 69-inch, and 4,000-ft of 66-inch PCCP (Smith and Bruny 2004).

Metropolitan Water District of Southern California (MWDSC): The Metropolitan Water District supplies water to 26 member agencies and serves a population of 19 million. They have a total of 820 miles of pipes and tunnels in their system, 163 miles of which is PCCP. Diameters of PCCP range from 42-inch to 201-inch. The major lines are typically 30 to 50 years old, with operating pressure of up to 300 psi. Like the SDCWA, the Water District has embarked on a multi-year condition assessment program of their PCCP lines, and has performed several miles of repair using primarily steel pipe Sliplining. Relining is being considered on a section of the Second Lower Feeder due to the importance of minimizing loss of internal flow area. Whenever other technologies are used, design is fully structural. PCCP is no longer installed in the system, and any pipe replacement is done with steel pipe.

City of Phoenix Water System: The City of Phoenix is the fifth largest City in the US, and has approximately 150 miles of PCCP water transmission mains, ranging in diameters of 42-inch through 108-inch. Following a catastrophic failure, the City embarked on a condition assessment program, and plans to eventually investigate all 150 miles of pipe. To date, they have completed 30 miles of the condition assessment, and are gearing up for the next 30 miles. 15 miles were on the Val Vista Line, while the remaining 15 miles included the Superior Waterline as well as other sections of the system. Substantial sections of the assessed pipes have been Sliplined and Relined with steel cylinders. Other technologies, such as CFRP repair, are considered a temporary solution, and are only utilized when emergency repair is needed in difficult access sections of their system. To date, the largest Relining program of PCCP with steel cylinders in the nation has been executed by the City. On the Superior Waterline, 3,300-ft of 60-inch PCCP was Sliplined with 56-inch steel pipe sections in 2006. On the Val Vista Line, 10,000-ft of 72-inch diameter PCCP was Relined with steel cylinders in 2005 and 2006; in 2009, 18,500-ft of 72-inch, 90-inch and 96-inch diameter of PCCP was Relined with steel cylinders. Another 40,000-ft of the Val Vista Line will likely be Relined/Sliplined with steel cylinders in the future.

CONCLUSION

At least five rehabilitation technologies exist for the repair and rehabilitation of PCCP. Emergency repair or difficult access conditions can limit the options available to an owner. For larger projects where fully structural or structurally independent solutions, described by AWWA M28 Class IV linings, are required, steel cylinder Relining or Sliplining provides a cost effective long term solution to the owner. Case histories and experience has shown that the steel cylinders can be manufactured, installed, welded and grouted into place, resulting in a permanent long-term structural renewal of the PCCP host line. In addition, the steel cylinders can be designed to compensate for decreased flow areas or increase the pressure requirements or capacity of a system, giving the owner added benefits to these proven methods of PCCP rehabilitation.

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