San Diego County Water Authority Aqueduct Protection Program since 1992: Evolution in Design and Construction of Steel Cylinder Relining of PCCP

Michael K. Kenny[1], Shah Rahman[2]

[1] Principal Construction Manager, San Diego County Water Authority, 4677 Overland Ave, San Diego, CA 92123; Tel: (760) 233-5298; E-mail: mkenny@sdcwa.org
[2] Central Regional Engineer, Northwest Pipe Company, 351 Longhorn Road, Saginaw, TX 76179; Tel: (909) 471-6095; E-mail: srahman@nwpipe.com

ABSTRACT

The San Diego County Water Authority (SDCWA) is a wholesale water supplier to 24 agencies in the San Diego, CA area, serving a population of more than 3.5 million. Approximately 82.5 miles of the total 300 miles of pipe in the system is Prestressed Concrete Cylinder Pipe (PCCP). 1979 marked the first catastrophic failure of a 19 year old section of PCCP. In order to ensure that the Water Authority fulfills its mission statement, "to provide a safe and reliable supply of water to San Diego County," the Aqueduct Protection Program (APP) was instituted in 1992 with a primary focus of preventing premature failure of the 82.5 miles of PCCP and extending the overall service life of the PCCP system. The initiatives undertaken by the Water Authority as part of the APP have been pioneering and have been closely followed by owners of PCCP systems both nationwide and around the world. The rehabilitation of the PCCP system comprises the use of collapsible steel cylinders as a long term structural solution, extending the service life of a line by 75 years.

This paper begins with a detailed look at the history and performance of PCCP in SDCWA's transmission system, which then leads into a historic review of the Aqueduct Protection Program, how and why it came into being, covering all substantial initiatives that have been undertaken to date. A clear understanding of the sustainable approach to extending the service life of the agency's PCCP lines is given. As a pioneer in the use of collapsible steel cylinders to achieve a fully structural renewal of deficient PCCP lines, the Water Authority has played a key role in the evolutionary development of the design and installation of these Steel Reliners. Design methods and technological developments have iteratively improved cylinder fabrication, installation processes, and quality control protocols, all of which are discussed. A case history of the on-going Pipeline 3 Relining, Sweetwater to Lower Otay, is provided to illustrate many of the topics discussed.

INTRODUCTION

The San Diego County Water Authority (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 2 aqueducts, comprising a total of 5 major pipelines that extend north to south of the County, with approximately 300 miles of pipe in the system. In order to ensure that the Water Authority fulfills its mission statement, "to provide a safe and reliable supply of water to San Diego County," the Aqueduct Protection Program (APP) was envisioned in 1991 and approved by the Board in 1992. Beginning with its first PCCP failure in 1979, a primary focus of the APP has been to prevent premature failure of the PCCP and to extend the overall service life of the PCCP system through rigorous condition assessment utilizing state-of-the-art technologies and, at the time, a 30-year goal to rehabilitate all 82.5-miles of PCCP with collapsible steel reline cylinders. To date, approximately half of the PCCP system has been structurally relined with steel cylinders.

Pipe materials in the 300-mile system consist of non-cylinder reinforced concrete pipe, reinforced concrete cylinder pipe, Prestressed Concrete Cylinder Pipe (PCCP), bar-wrapped concrete cylinder pipe and steel pipe, with internal diameters ranging from 48-inch to 108-inch. Between 1959 and 1982, 82.5 miles of large diameter PCCP were installed along the Second Aqueduct and Crossover Pipeline. All post-1984 pipeline construction has been with bar-wrapped concrete cylinder pipe, reinforced concrete cylinder pipe and steel pipe only. All urgent removal and replacement of deficient PCCP sections have also been done with steel pipe.

HISTORY OF PCCP IN THE SDCWA SYSTEM

Prestressed Concrete Cylinder Pipe (PCCP): Invented as an alternative to steel pipe during WWII due to steel shortages, PCCP is a composite pressure pipe that uses the tensile strength of prestressed steel wires and the compressive strength of concrete, to compensate for the strength provided by steel alone. A very thin steel cylinder, typically 16 GA/0.0598-inch, in PCCP serves as a water membrane (Najafi et al., 2013). The very first PCCP project in the US was installed in 1942 (AWWA 2007). In the western US, PCCP was first used in the early 1950's (Troyan et al. 2013). There are two types of PCCP; embedded cylinder type which consists of the prestressing wires placed around the concrete core, and the lined cylinder type where the prestressing wire is wrapped directly around the steel cylinder. 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 in1955, and became more noticeable in the early 1980's (Goldstein 2009). These failures "have presented 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 (Rahman et al. 2012)."

Characteristics of Water Authority's PCCP System: Along the Second Aqueduct, the Water Authority has 82.5 miles of PCCP, installed between 1959 and 1982. The first PCCP line was operational in 1960 and was 30 miles in length. Core thicknesses of PCCP throughout the 82.5-mile system vary based on operating pressures. The joints utilized are primarily the Carnegie type, with bell and spigot joint rings welded on to the thin steel cylinder membranes, and sealed using O-ring gaskets. In high pressure locations, the Carnegie joints were welded together, with steel tension rods secured to the bell and spigot rings by welding, and also through the use of steel clamps (Troyan et al. 2013). Thin steel shorting straps were developed and incorporated into embedded cylinder type PCCP in the late 1970's to allow for cathodic protection, but 72-miles of the Water Authority's 82.5-mile PCCP system does not have shorting straps as they were installed prior to the development of shorting straps. Economical cathodic protection of the PCCP system is therefore not possible.

Failure History: To date, the Water Authority has experienced a total of 12 PCCP failures, 7 of which were catastrophic in nature, Table 1, and the other 5 were various types of major leaks (Faber et al. 2012). The first catastrophic failure took place in 1979, followed by two more in 1980 and 1982. There would be an additional four catastrophic failures, with the most recent being in 2008, Table 1 (Faber 2014).

Table 1: Catastrophic PCCP Failures at San Diego County Water Authority

Failure Year	Diameter	Pressure	Year Installed	Repair Solution
1979	66-inch	170 psi	1960	Removed and replaced with Steel Pipe
1980	66-inch	175 psi	1960	Steel bands around pipe and grouted.
1982	66-inch	170 psi	1960	Steel bands around pipe and grouted
1990	84-inch	70 psi	1974	Removed and replaced with Steel Pipe
1993	96-inch	300 psi	1972	Removed and replaced with Steel Pipe
2006	66-inch	125 psi	1960	Removed and replaced with Steel Pipe
2008	72-inch	260 psi	1977	Removed and replaced with Steel Pipe

Information summarized from Faber (2014)

In the early 1980's, PCCP failures were dealt with by replacing the damaged sections of pipe with steel pipe. As a long-term solution, the Water Authority would have to remove and replace all deteriorating PCCP. To deal with "time, right-of-way issues, environmental considerations, cost, and other constraints," associated with constructing new pipelines to replace failing ones, the Water Authority developed the steel relining technology in 1982 (Stine and Stift, 1998). From 1982 to 1985, rehabilitation of 5 miles of the distressed PCCP line was conducted using steel cylinders. In the late 1980's, the Water Authority relined 1.5 miles of the 72-inch Shepherd Canyon Pipeline for the City of San Diego.

THE AQUEDUCT PROTECTION PROGRAM

Until the catastrophic failure of 1990 occurred on a PCCP section that was only 16 years old, it was believed that corrosion issues which led to the previous three catastrophic failures were restricted to one particular section of the PCCP line (Faber 2014). The new failure resulted in costly damages, tremendous inconvenience to the public and received wide media coverage. Also, by this time, it was recognized that PCCP failures were more than an endemic problem as Owners were facing similar challenges nationwide. In 1991, the Water Authority became one of founding utilities of the PCCP Users Group, a collection of Owner Agencies intent on evaluating and understanding the issues related to the recurring catastrophic failures in their transmission systems.

In 1992, the Water Authority Board of Directors approved the creation of the Aqueduct Protection Program (APP) with the goal to inspect and evaluate all the PCCP in its system to establish remaining service lives using state-of-the-art condition assessment technologies, to be followed by necessary structural rehabilitations. In 1993, another PCCP section that was only 21 years old, failed catastrophically. The Relining and Pipe Replacement Program was approved by the Board in 1994. By 2006, the program budget was $455 million; in 2007, the budget was raised to $787 million. Through the APP, a part of the Water Authority's Capital Improvement Program initiated in 1989, preventative maintenance is performed on the PCCP lines and other facilities to ensure the regional pipeline system remains reliable and all necessary equipment upgrades, modifications, and improvements are made. In 2009, the Board approved the Asset Management plan which established the Asset Management Program. Part of the plan included making APP part of the Asset Management Program.

State-of-the-Art Assessment Technologies: The history of the APP has been about the utilization of state-of-the-art condition assessment technologies and combining it with long-term fully structural rehabilitation technologies to substantially extend the service life of the 82.5 miles of

PCCP in the system. Throughout its existence, the APP has kept pace with technological developments in the pipeline condition assessment industry. Starting out primarily with visual and sounding techniques for the assessment of the PCCP system, the Water Agency has been a pioneer in the adoption of new technology that has made its condition assessment efforts progressively more precise. Adoption of eddy current electromagnetic inspection methods in the late 1990's were supplemented later with a more advanced acoustic monitoring program using hydrophone arrays. In 2006, the first 7.5 miles of Acoustic Fiber Optics (AFO) technology was installed that provided real-time monitoring of PCCP sections by detecting wire breaks round the clock. By 2009, 47 miles of the PCCP system was fitted with AFO systems.

Table 2 shows some of the major initiatives that have been undertaken, and significant events that have occurred in the history of the APP from 1999 to present.

Table 2: Aqueduct Protection Program (APP) Highlights 1999-2013

Year	Major Initiatives/Events of the Aqueduct Protection Program
1999	Up to this point, $6 million of inspection and repairs performed since 1992. Inspection methods primarily visual and sounding to this point; supplemented with non-destructive technologies such eddy current electromagnetic inspection technologies. Section of distressed 69-inch PCCP was discovered in March 1999 in Pipeline 3 in Rancho Peñasquitos.
2000	Inspections conducted on more than 25 miles of PCCP. APP team was invited to be keynote speakers at a UNESCO (United Nations Education, Scientific, and Cultural Organization)-sponsored conference on PCCP in Paris, France. 3 miles of Pipeline 3 shutdown from Black Mountain south to Miramar Hill in Rancho Peñasquitos, and 28 locations dug up to allow for external inspections; plans made for steel cylinder relining
2001	Inspection of 29 miles of PCCP. Two portions of Pipeline 3 along the Second Aqueduct in inland North County found to need immediate repairs, sections removed and replaced. 2,350 ft of Pipeline 4 in Rancho Peñasquitos relined with steel cylinders. The Pipeline Condition Assessment Report provided condition report of all lines installed prior to 1984.
2002-2003	Inspection of 54.45 miles of the Second Aqueduct conducted during six planned shutdowns. Condition assessment for Second Aqueduct and Crossover Pipeline completed, enabling estimation of remaining service life of lines constructed before 1982. The Aqueduct Corrosion Monitoring and Assessment Program developed from Operating Budget to perform annual corrosion-related tasks on the Second Aqueduct-Crossover Pipeline and 1987 pipelines. APP objective also expanded to include assessment of the First Aqueduct and the Tri-Agencies Pipeline, and provide support to CIP projects, ROW management, and the PCCP Relining/Replacement Program.
2004	Largest pipeline shutdown season in Water Authority's history up to this point --- 5 scheduled shutdown, 2 unscheduled shutdowns, covering 61.4 miles of pipe. Inspection conducted on ten different sections of the First and Second Aqueducts, including both treated and untreated water pipelines and related facilities. 8 urgent repairs conducted. Warranty inspections also performed. Completion of the 6.3 mile Rancho Peñasquitos / Mira Mesa (Pipelines 3 & 4) steel relining project
2005	Inspection of 55 miles of PCCP, through three scheduled shutdowns; included seven different sections of the First and Second aqueducts; discovered and repaired one section of PCCP in Pipeline 4. Acoustic monitoring program was implemented by deploying 6 hydrophone arrays over 4.5 mile PCCP section, resulting in the discovery of 19 wire breaks during the year. Hydrophone system also prevented third party damage when it coincidentally detected a Contractor digging into the ground directly on top of 200 psi PCCP line.

2006	Inspected 51 miles of regional aqueduct system through four planned shutdowns; found and repaired two distressed pipeline sections. Installation of first Acoustic Fiber Optic (AFO) monitoring system inside sections of Pipelines 3 and 4; 7.5 miles installed. Deployed first remotely operated vehicle inside Pipeline 3 and 4 for inspection. Steel cylinder relining of 5.2 miles of Pipeline 4 from Del Dios Highway to Black Mountain Ranch. In May 2006, failure occurred on a 66-inch PCCP section in Pipeline 3 at Mission Trails Regional Park, just prior to its scheduled relining. Construction of Jackson Drive Crossover emergency line allowed for portions of Line 3 to remain out of service while condition assessment was conducted and repairs made. APP had become a $455 million program at this point.
2007	Inspections were conducted on 40 miles of pipeline, through six scheduled and five unscheduled shutdowns. Additional 7.5 miles of fiber optics (AFO) were installed in Pipelines 3 and 4, bringing total number of miles of AFO cables to 15 miles. Since 1982, 21.4 miles of PCCP had been relined with steel cylinders at this point. APP had become a $768 million program at this point.
2008	Completion of 2 mile steel cylinder relining of Pipeline 4 from Pain Mountain, Elfin Forest to Del Dios Highway, Rancho Santa Fe. Completion of 3 mile reline with steel cylinder of Pipeline 3 from Mission Trails to Lake Murray Relining Project. 15 miles of AFO cables added, bringing total length to 30 miles. Another catastrophic failure occurred in a 72-inch PCCP line. Failure of a high-pressure, 72-inch PCCP line.
2009	The Board approved the Asset Management plan which established the Asset Management Program. Part of the plan included making APP part of the Asset Management Program. Visual inspection of 47 miles of pipelines conducted during planned annual shut downs. Amount of AFO cables installed totals 47 miles.
2010	American Public Works Association (APWA) Project of the Year Award for Relining and Pipe Replacement Program; APWA Award for Pipeline 4 Emergency Shutdown and Repair in Mission Trails Regional Park.
2012	Completion of 3 miles of steel cylinder relining of Pipelines 3 and 4 from Miramar Hill to Scripps Ranch. Total of 30.3 miles of PCCP relined with steel cylinders to this point since 1982.
2013	Completion of 3.8 miles of 72-inch diameter PCCP relining with steel cylinder from Mission Trails to Lake Murray. APWA Project of the Year Award for Miramar Hill to Scripps Ranch Relining Project; also received APWA Award of Excellence. In late 2013, relining of 5.4 miles of PCCP from Sweetwater in Bonita to Lower Otay Reservoir in eastern Chula Vista was begun and is expected to be completed in summer 2014.

Information for this table compiled primarily from SDCWA (1999-2013) Annual Reports. Also from Galleher et al. (2007), Faber et al. (2012), and Troyan et at. (2013)

PCCP MANAGEMENT – THE SUSTAINABLE APPROACH

The primary strategy employed by the Water Authority's Asset Management Program (AMP) for the management of a prematurely failing PCCP system has been a risk-based approach, with an emphasis on the most prudent way in which money is spent to select the most appropriate rehabilitation technique, making the overall approach a sustainable one. This sustainable approach takes into account factors beyond just wire breaks that lead to PCCP failures, the limitation of wire break identification and information, and considering rehabilitation options based on the consequences of a failure (Faber et al. 2012). Combining condition assessment and real-time AFO monitoring to identify potential areas of risk, the AMP is able to determine how best to utilize its relining program budget to mitigate associated risks of failure with longer segments of the system rather than focusing only on one or two sections of particularly distressed pipe. The sustainable approach enables the Water Authority to determine when to use a localized repair, versus a comprehensive repair of long sections, based on risk of failure and associated Lifetime Total Costs.

This approach however diverges from recent industry approaches, which puts a high emphasis on broken prestressing wires to quantify the risk of damage to a pipe section, followed by the performance of only "isolated [or localized] repairs on sections of pipe experiencing advanced deterioration (Higgins et al. 2012)." Baird (2011) summarizes this philosophy, explaining that by combining electromagnetic, sonic/ultrasonic, and visual and sounding inspections, it is possible to arrive at a pipe risk management strategy which then enables an Owner to target "future inspections, and [repair] or [replace] *individual pipe segments* before failure." From the experience of the Water Authority, the latter approach fails to address two key issues, and should not therefore be the only way in which to manage a PCCP system:

a) besides wire breaks (which is what condition assessment technologies identify), there are other reasons why PCCP lines fail, even though broken wires are known to be one of the primary reasons for failure – this includes joint problems, surge events, manufacturing defects, thrust forces, cylinder defects, hydrogen sulfide related internal corrosion, improper design, third party damage, etc. (Romer and Bell, 2008). The Water Authority has experienced joint-related failures of PCCP in addition to failures connected to broken wires
b) limitations on the assessment of wire breaks – it is not possible to assess wire breaks near joints; if signals are not properly calibrated and if accurate records are not supplied by an Owner, then the number of wire break predictions are less than accurate. Also, additional wire breaks may occur when a PCCP line is being dewatered or refilled (Faber et al. 2012)

Faber et al. (2012) provide an extensive analysis of the sustainable approach used by the Water Authority, which incorporates both risk and cost considerations when selecting a rehabilitation method, led primarily by assessing the consequences of a failure. Consequences of failure are influenced by:

1) location of the distressed section (e.g. in a rural area, or in an urban area … and what would be the consequences of flooding in the given vicinity? .. high or low?)
2) hydraulics and operation of the pipeline (can a section of PCCP that operates under gravity flow handle temporary pressurized flow in emergency conditions? … "a complete rehabilitation method [must be selected] to reduce the consequence of failure and risk under normal operation and mitigate any additional risk during an emergency condition")
3) system redundancy (due to the size of these critical primary transmission lines, there is little redundancy, so shutdowns for repairs without inconveniencing homes and businesses are very limited, making multiple or sporadic shutdowns for *localized repairs* a challenge)

Rehabilitation methods employed by the Water Agency include:

a) Localized Repairs, where they remove and replace section of PCCP with steel pipe, or use Carbon Fiber Reinforced Composites, CFRP; the latter method is not considered a permanent solution since it is a relatively new technology. CFRP is used for emergency repairs or in select areas where steel relining is not practical. The cost of CFRP repair is approximately $7,500/lf, making it prohibitive compared to steel relining which is $1,300/lf (Troyan et al., 2013);
a) Comprehensive Repairs, where fully structural rehabilitation of long sections of a PCCP line is performed with collapsible steel cylinder reliners

The Sustainable Approach Example: Faber et al. (2012) illustrate the decision making process when determining whether to employ localized repair or comprehensive repair of longer segments of a PCCP line; their example includes a Pipeline A which is 12 miles in length and was installed in

1960, and a Pipeline B which is 11 miles in length and was installed in 1982. Tables 3 and 4 summarize information about both pipelines. Both lines are currently fitted with AFO and are therefore continuously monitored in real time. Pipeline A has had 4 failures, 3 of which were due to wire corrosion and breaks. Pipeline B has had no failures.

Table 3: Condition Summary of Pipelines A and B

Name	Length (miles)	Year Installed	Install Condition	Joint Mortar	Surge Potential	Broken Wires	Wire Breaks	No. Failures
Pipeline A	12	1960	Poor	Poor	Low	15 %	180/yr	4
Pipeline B	11	1982	Moderate	Acceptable	Moderate	1%	10/yr	0

Table 4: Consequence of Failure of Pipelines A and B

Name	Length (miles)	Year Installed	Location	Hydraulics	Redundancy
Pipeline A	12	1960	Urban – Critical Infrastructure Nearby	Gravity – no emergency pumping	Limited
Pipeline B	11	1982	Rural	Gravity – no emergency pumping	Limited

Risk Analysis: With RISK being a product of *condition* and the *consequence of failure*, it can be concluded from the above tables that the risk associated with Pipeline A is the higher one of the two lines. Pipeline A is in relatively poor condition and is located in an urban area, so the consequences of a failure are high; Pipelines B is in better condition when considering joints, wire breaks, and wire break activity than Pipeline A, and being in a rural area, the consequences of a failure are relatively lower.

Cost Analysis: To analyze cost differences between localized repairs versus comprehensive rehabilitation, a 3-mile section was selected in line A which had a 9 percent distress rate. This meant 9 percent of pipe sections in the 3-mile segment had at least one wire break, which would continue to deteriorate over the next 50 years.

For **localized repair** analysis, it was assumed that 1,440-ft of pipe, or 9 percent of 3 miles, would be repaired as needed based upon a certain number of wire breaks threshold, over the next 50 years. Table 5 shows how 20-ft sections of PCCP in this segment would be repaired.

Table 5: Assumed Number of Repairs/Year in Line A through Remaining 50-yr Lifespan

Rate of Repair	Years	Number of Repairs	Distance Repaired (feet)
1 repair / 2 yrs	2011 thru 2020	5	100
1 repair / yr	2021 thru 2038	18	360
2 repairs / yr	2039 thru 2055	34	680
3 repairs / yr	2056 thru 2060	15	300
Total		72	1,440

Assuming a range of annual price escalation and inflation, combined between 2.5 percent and 5 percent, the localized repair approach would cost between $45 million and $110 million. Not included in Faber et al. (2012) analysis was the additional maintenance cost for acoustic monitoring

(AFO), which with escalation and inflation, combined between 2.5 percent and 5 percent, would amount to $4 million to $8 million over a 50-year period.

For the **comprehensive rehabilitation** method, the fully structural rehabilitation of the entire 3-mile segment with steel cylinders would be $29 million at present cost analysis. Using bond financing for a 30-year lending period, the total cost for this approach would be $60 million. Table 6 summarizes the 50-year Lifetime Total Cost of each rehabilitation approach for Pipeline A.

Table 6: 50-Year Lifetime Total Cost Analysis, of Pipeline A

Rehabilitation Approach	Length of Line Rehab	Interest or Escalation plus Inflation Rate	Lifetime Total Cost	Additional Cost of AFO Maintenance
As-needed Localized	1,440-ft	2.5%	$45 million	$4 million
As-needed Localized	1,440-ft	5%	$110 million	$8 million
Comprehensive	3 miles	5%	$60 million	0

Risk Reduction: Based on this example, Faber et al. (2012) conclude that with the localized repair approach, risk reduction would occur only in the 1,440-ft of the 3-mile section considered. With RISK being a product of *condition* and *consequence of failure*, the risk would not be reduced in the remainder of the 3-mile section as other segments of PCCP could deteriorate, and the consequence of failure or multiple failures would cost substantially more. Furthermore, other reasons for failure such as joint problems, manufacturing problems, surge events, etc., besides just wire breaks, would still present a formidable risk in the remaining sections of the 3-mile segment after 50 years. With the comprehensive approach on the other hand, which would rehabilitate the entire 3-mile segment, "the overall risk would be significantly reduced due a significant mitigation of additional condition factors (joint conditions and installation defects) and the consequence of failure factors."

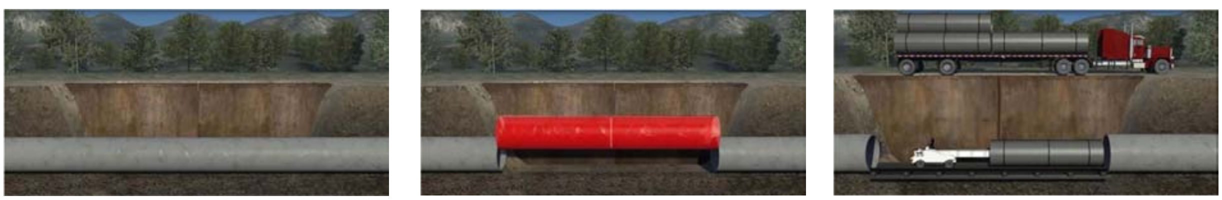
The Sustainability: As can be seen from this example, the more sustainable approach for dealing with the 50-year lifecycle of Pipeline A would be comprehensive rehabilitation in terms of cost and reduction of risk. For the 1 percent distressed Pipeline B, on the other hand, the localized rehab option is more sustainable from a cost standpoint at this point, costing $11.1 million to $11.8 million depending on escalation and inflation. While RISK is at an acceptable level for Pipeline B at this time, based on condition and consequence of failure, and the continued use of AFO, an important aspect of the sustainable approach, may indicate that a comprehensive rehabilitation approach is needed in the future.

STEEL CYLINDER RELINING

Development of Steel Cylinder Relining at SDCWA: As stated earlier, the Water Authority developed the steel cylinder relining process for the fully structural rehabilitation of distressed PCCP in the early 1980's, and by 1985, approximately 5 miles of PCCP had been relined with this process (Stine and Stift, 1998). The process essentially rebuilds distressed PCCP internally using a series of collapsed steel plate liners which are inserted into the host pipe, re-rounded, and welded into place to create a new steel pipeline inside the PCCP. The Water Authority's Assistant Chief Engineer at the time, Buckley L. Ogden, is credited with developing the process in the Escondido, CA operations yard (Troyan et al. 2013). Ogden was also a Captain in the US Navy Reserves Civil Engineer Corps, worked for the Salt River Project in Phoenix, AZ from 1958-1963, and served the Water Authority from 1966 to 1984. He retired from the Navy in 1990, and passed away in May 1997 (The Navy Ring, 1997). Captain Ogden is also credited with developing a pipe carrier cart which would pick up the collapsed reliners, drive them into place inside the host PCCP for fit-up and welding, and subsequent grouting of the annular space. This earliest process has continued to evolve since the 1980's, as steel plate manufacture, pipe-making capabilities, and welding technology have advanced, along with the refinement of QC methods; fit-up tolerances have been tightened, designs improved, and contractors have continued to make the installation process more efficient.

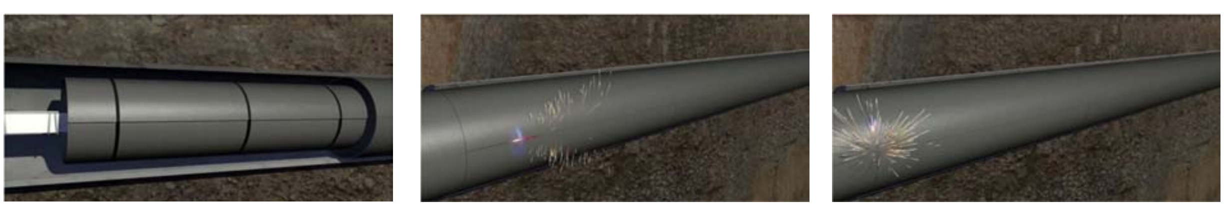
Steel Liner Design Parameters: Internal pressures and D/t ratio per AWWA M-11 (2004) governs thickness determination. External loading based on depth of existing host pipe depths; modulus of soil reaction, E', of 3000 psi for the existing PCCP as backfill is assumed.

Relining Process: Rahman et al. (2012) provide a brief overview of the collapsed steel cylinder relining process. PCCP relining begins with gaining access to the host PCCP line by excavating portals approximately 100-ft by 40-ft, depending on whether they're shored with steel plates or sloped excavations, Figure 1a. This is followed by the permanent removal of two 20-ft sections of PCCP, giving access to the host pipe in either direction from the portal, Figure 1b. Pipe carrier carts, usually proprietary to the installation contractor, are then used to transport the collapsed steel reliners which are bound with steel straps to hold them in a collapsed state, into the host PCCP, Figure 1c.



Figures 1a, b, c: Portal Excavation, Removal of 2 PCCP sections, Transport of Reliners into Pipe

As each reliner is placed at the appropriate location in the host pipe, the fit-up of that section, and adjacent sections, begins. Each section is first re-rounded by cutting of the steel straps holding it in its collapsed state, Figure 2a, followed by the use of hydraulic rams and jacks for precision fit-up. Fit-up tolerances are very tight per Water Authority specifications, to ensure the highest quality of installation. Tack welds initially hold the cylinders into place when the specified positions are achieved inside the host PCCP. Permanent welds are then applied in the form of full-penetration welds along the longitudinal seams of the cylinder, Figure 2b, and full fillet welds circumferentially to join the bell-and-spigot joints of adjacent sections of reliners, Figure 2c.



Figures 2a, b, c: Removal of Steel Bands, Full Penetration Longitudinal Seam Welding, Full Fillet Circumferential Joint Welding

The annular space between a fitted liner and the host PCCP, typically 1 to 2-inches, is pressure-grouted with a lightweight cellular grout through threaded grout ports pre-fabricated on the liners; this prevents corrosion of the outside of the cylinder and also adds structural integrity to the steel cylinder-host PCCP system. To protect liners from buckling, 2-inch to 3-inch wide grout rings are installed periodically by welding to the host PCCP Carnegie rings at joints during fit-up; these grout rings serve as grout bulkheads, partitioning off the annular space into sections, which then serve to control external grouting pressures. After the grouting operation, grout plugs secure the ports. Internal corrosion protection of the relining system is then provided by in-field application of cement mortar lining using a centripetal spray system. To complete the relining, new steel pipe sections are installed at the portal site, Figure 3a. Reinforced steel and concrete are placed around the new sections of steel pipe, Figure 3b, and the portals are finally backfilled, Figure 3c.

Figures 3a, b, c: New Steel Pipe Sections Placed at Portal where 2 Sections of PCCP was Removed, Reinforced Steel and Concrete around New Pipe, Portal Backfilled

PROJECTS COMPLETED

To date, approximately 39.3 miles, or 48 percent of the overall PCCP system has been relined with steel cylinders. Table 7 lists provides a partial listing of steel relining projects that have been successfully completed, as well as others that are on-going, or planned for the future.

Table 7: Select Steel Relining Projects of the APP

Project Name	Year	Length	Host PCCP Internal Dia.
Rehabilitation of Pipeline 3	1982-1985	5 miles	66-in
Shepherd Canyon Pipeline Reline Project (City of San Diego, performed by SDCWA)	1989	1.5 miles	72-in
Pipeline 3 – Relining in Rancho Peñasquitos	2001	0.45 miles	69-in
Rancho Peñasquitos / Mira Mesa (Pipelines 3 & 4)	2004	6.3 miles	96-in, 72-in, 69-in, and 66-in
Pomerado Relining Project (Pipeline 4)	2005	5 miles	69-inch, 84-inch
Del Dios HW to Black Mountain Relining Project (Pipeline 4)	2006	5.2 miles	96-in
Paint Mountain to Del Dios Highway (Pipeline 4)	2008	2.3 miles	96-in
Relining Under I-15 Project (Pipelines 3, 4, & 4A)	2008	0.43 miles	72-in
Miramar Hill to Scripps Ranch (Pipelines 3 & 4)	2012	3 miles	72-in and 96-in
Mission Trails Park to Lake Murray (Pipeline 3 &4)	2013	3.5 miles	66-inch, 69-inch
Sweetwater to Lower Otay (Pipeline 4)	Summer 2014	5.4 miles	69-inch
Pipeline 3 Desalination Relining† (Retrofitting of a steel water pipeline for higher pressures)	Jan 2014 – Summer 2015	5.1 miles	72-inch, 75-inch
San Luis Rey River Relining (Pipelines 3, 4, & 5)	Fall 2014 – Summer 2015	1.4 miles	75-in, 90-in, and 96-in

†*The Pipeline 3 Desalination Relining Project is unique in that this project is relining an existing Steel pipeline with steel cylinders in order to upgrade/retrofit it to handle higher pressures between San Marcos and Twin Oaks once the Carlsbad Desalination plant comes online*

MANUFACTURE OF STEEL RELINERS

Fabrication of the collapsible relining cylinders begins with the ordering of steel plates by the pipe manufacturer. On the Sweetwater to Lower Otay (Pipeline 3) project, discussed as a case history in the next section, steel plates were ordered to "ASTM A36 Grade 36, modified to have rninimum yield strength of 40,000 psi." Steel plates were first cut to required lengths and widths on a burn table, Figure 4a. The programmable burn table squared the ends of the steel plate, cut holes for grout couplings in assigned locations on the steel plates, Figure 4b, created any required miters, and locations for spacer blocks and back-up bars were marked on the plate using an arc tracer. Other items etched on the surface included orientation of the steel plate, Figure 4c, and grids for placing pertinent technical information on each cylinder, Figure 4d.

Figures 4a, b, c, d: Burn Table, Hole Cut for Grout Coupling, Orientation Etch, Grid Etched for Technical Information on Each Reliner Section

Plates were then rolled into cylinders of required diameters using a pyramid-type roller, Figure 5a, and tack welds placed along the longitudinal seam to hold the liner into shape. Two pieces of rolled cylinders where then fitted up for girth seam welding, resulting in the specified length of reliner, Figure 5b. Full penetration submerged arc welding was required for all girth seams; all sub-arc welds were required to be either x-rayed or undergo real time radiography. On the end of the cylinder where the weld bell was to be formed, the longitudinal seam was then welded to allow for belling to take place, Figure 5b. A bell was then formed using a hydraulic expander at the end of the cylinder where the seam weld was completed for belling, Figure 5c, and d.

Figures 5a, b, c, d: Pyramid-type Rollers for Plate Rolling, Girth-seam Welding of two Sections of Reliner, Hydraulic Expander for Belling, Completed Bell

Backup bars were made at previously etched sections of the plates, Figure 6a, and b; backup bar welds were tested using dye-penetrant. Backup bars were then stitch cut to prepare for the overlapping of the longitudinal seams for the collapsing of the reliners, Figure 6c. Spacer blocks were welded on the reliners, as were grout couplings in the previously cut holes; dye-penetrant testing was completed on each welded item, Figure 6d.

Figures 6a, b, c, d: Preparation for Backup Bar Forming, Completed Backup-Bar with Dye-Penetrant Testing Complete, Stitch Cutting of Backup Bar Prior to Collapsing, Dye-Penetrant Testing of Welded Spacer Blocks and Grout Couplings

The final steps included collapsing the cylinders, Figure 7a, tie bars being welded internally, Figure 7b, and steel straps placed around the outside to ensure that the liner would remain in the collapsed state, Figure 7c, until re-rounded in the field by removal of both the steel straps and the tie bars during installation. Steel reliners were now ready for storage and transportation to the project site.

Figures 7a, b, c: New Steel Pipe Sections Placed at Portal where 2 Sections of PCCP was Removed, Reinforced Steel and Concrete around New Pipe, Portal Backfilled

CASE HISTORY – SWEETWATER TO LOWER OTAY RELINE PROJECT

The Sweetwater to Lower Otay Pipeline Relining Project was awarded in late 2013 to LH Woods and Sons, Inc.; Northwest Pipe Company was the low bidder as the steel relining material supplier. This project involved the structural relining of approximately 5.5 miles of a 69-inch internal diameter PCCP line that traverses portions of the communities of Bonita and eastern Chula Vista (Eastlake, Otay Ranch, as well as the Otay Ranch Preserve and Lower Otay County Park). Figure 8a shows the regional location map, as well as a project vicinity map as an insert, highlighting the pipeline and location of the portals for the relining project. Steel cylinders were manufactured to an outside diameter of 66-inch, and had a wall thickness of 3/8-inch (0.375-inch). While the initial plans were made for 17 entry portals, the Contractor was able to reduce the number of actual portals to 11, without causing any installation problems on the project. The remaining portals served as access shafts, allowing for man and other equipment entry. Figures 8b shows pertinent design details for the steel reliner cylinders on this project.

The process utilized for this relining project was essentially performed as described previously in this paper. 11 full size portals were made to enable the removal of 40-ft, or two sections of the host PCCP, Figure 9a. Once reliners were lowered into the portal, Figure 9b, removal of the two sections of pipe facilitated man-entry into the host pipe as well as insertion of collapsed steel reliners, Figure 9c. Full size portals were located at points 1, 3, 4, 5, 7, 8, 10, 12, 14, 16 and 17, shown in Figure 8a.

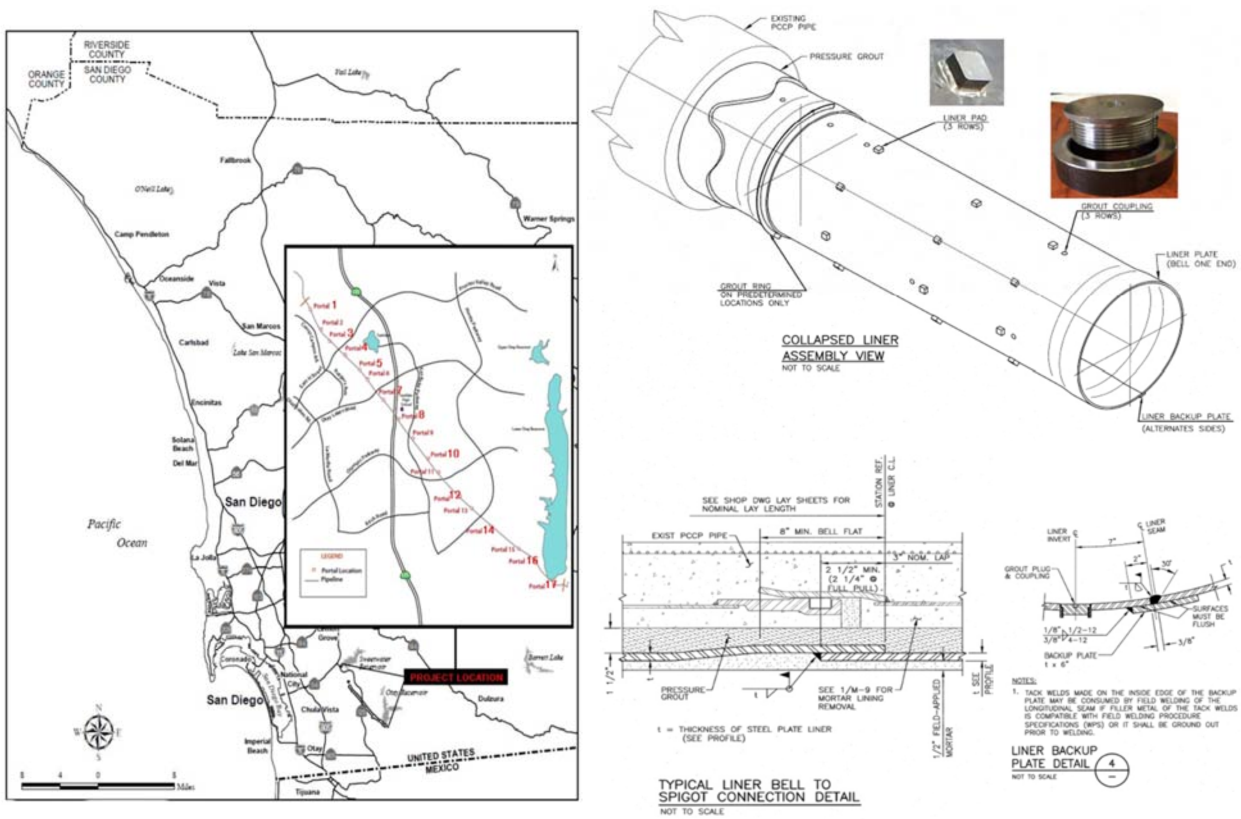


Figure 8a, b: Regional Vicinity Map & Project & Portal Locations, Pertinent Design Details

Figures 9a, b, c, d: Portal with 2 Sections of Host PCCP Removed, Steel Reliner being Lowered into Portal, Insertion of Reliner Section into Host Line on Pipe Carrier Cart, Installed Grout Ring

Welders were able to fit up and weld up to 700-ft of reliners/day. For the 20-ft sections of reliners, about a dozen tack welds were placed longitudinally and circumferentially as part of the fit-up process. Based on grout density and the use of 14-ft lift heights, the number of grout rings (means by which grouting pressure is controlled to prevent buckling of steel cylinders), which was originally numbered at 290 for the entire project, was cut in half. This directly affected installation productivity rates since subsequent liner installations beyond a ring must wait until grout rings have been fit up, welded and tested using dye penetrant. Figure 9d shows a grout ring in place.

One of the unique attributes of the project was the Quality Control equipment employed for weld testing of longitudinal seam welds in each steel cylinder; the Water Authority specified the use of Phased Array Ultrasonic Testing (PAUT) technology. PAUT is a specialized type of ultrasonic testing that uses multi-element array transducers and software to steer high frequency sound beams through the test piece and maps returning echoes, producing detailed images of internal structures similar to medical ultrasound imaging. While traditional UT uses multiple probes to effectively model a profile because a sound wave must be transmitted at various points to accurately detect defects, PAUT uses a single probe to transmit a projection so that multiple scans are not required. Unlike traditional UT where points of reflection and complex geometrical configurations are needed to provide sufficient scanning area, PAUT eliminates this need by digitally transmitting the source of the scan. This technology scans a greater area, is efficient and has greater accuracy and results in less user error compared to other NDT technologies.

Upon completion of liner installation, internal corrosion protection was provided by the application of in-field cement mortar lining. The Sweetwater to Lower Otay Pipeline Relining Project is anticipated to be completed in Summer 2014.

CONCLUSION

The San Diego County Water Authority has been a leader in the management of it prematurely failing PCCP system. In 1992, the Water Authority Board of Directors approved the creation of the Aqueduct Protection Program (APP) with the goal to inspect and evaluate all the PCCP in its system to establish remaining service lives using state-of-the-art condition assessment technologies, to be followed by necessary structural rehabilitations. A 30-year program has been instituted to rehabilitate all 82.5 miles of the PCCP system with collapsible steel cylinder reliners. The primary strategy employed by the APP for the management of its PCCP system has been a risk-based approach, with an emphasis on the most prudent way in which money is allocated to select the most appropriate rehabilitation technique, i.e. a localized repairs versus comprehensive repair. Risk of a failure is determined using the condition of a segment of the PCCP system and the consequences of a failure, while cost analysis for the selection of the appropriate rehab technology is determined using a Lifetime Total Cost approach.

Following the first catastrophic failure of it PCCP system in 1979, the Water Authority's Assistant Chief Engineer, Buckley L. Ogden, developed the collapsible steel cylinder relining process. By the mid-1980's, more than 5 miles of PCCP had been structurally rehabilitated using the method. To date, approximately 39.3 miles, or 48 percent of the overall PCCP system has been relined with steel cylinders, extending its service life by 75 years. The Water Authority has played a key role in the evolutionary development of the design and installation of steel cylinder relining. Design methods and technological developments have iteratively improved cylinder fabrication, installation processes, and quality control protocols, and serves as a model for other PCCP owners nationwide for their rehabilitation needs.

REFERENCES

American Water Works Association (AWWA). (2004). "Steel Water Pipe: A Guide for Design and Installation (M11)." AWWA-M11, Denver, CO.
American Water Works Association (AWWA). (2007). "Prestressed Concrete Pressure Pipe, Steel-Cylinder Type." AWWA C301-07, Denver, CO.

Baird, G. (2011). "Reducing Capital Budgets through pipe Segment Replacement Planning and Acoustic Monitoring." *Journal AWWA*, 103(4), 30-33.

Faber, N., Coghill, M., and J. Galleher (2012). "Beyond the Wires: A Sustainable Approach to Prestressed Concrete Cylinder Pipe Management." ASCE Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance—Doing More with Less, R. Card and M. Kenny, eds., American Society of Civil Engineers, Reston, VA.

Faber, N. (2014). "Large Diameter Pipe Failures Bring Over Fifty Years of Improvement." ASCE Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability, S. Rahman and D. McPherson, eds., American Society of Civil Engineers, Reston,VA.

Galleher, J., Holley, M., Shenkiryk, and G. Eaton (2007). "San Diego County Water Authority's Aqueduct Protection Program." ASCE Pipelines 2007: Advances & Experiences with Trenchless Pipeline Projects, L. Osborn and M. Najafi, eds., American Society of Civil Engineers, Reston, VA.

Goldstein, W. (2009). "WSSC Endangers Us by Failing to Confront the PCCP Problem," Maryland Politics Watch, < http://maryland-politics.blogspot.com/2009/01/wssc-endangers-us-by-failing-to.html> (March 16, 2014)

Higgins, M., Stroebele, A., and S. Zahidi (2012). "Numbers Don't Lie, PCCP Performance and Deterioration Based on a Statistical Review of a Decade of Condition Assessment Data." ASCE Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance—Doing More with Less, R. Card and M. Kenny, eds., American Society of Civil Engineers, Reston, VA.

Najafi, M., Mielke, R., Ramirez, G., Keil, B., Davidenko, G., Rahman, S. and A. Jain (2013). "Design, Analysis and Full-Scale Testing of the Rolled Groove Gasket Joint System in AWWA C303 Bar-Wrapped, Steel Cylinder Concrete Pressure Pipe." ASCE *J. Pipeline Systems Engineering and Practice*, 4(4), 56-69.

Rahman, S., Smith, G., Mielke, R., and B. Keil (2012). "Rehabilitation of Large Diameter PCCP: Relining and Sliplining with Steel Pipe." ASCE Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance—Doing More with Less, R. Card and M. Kenny, eds., American Society of Civil Engineers, Reston, VA.

Romer, A., and G. Bell (2008). *Failure of Prestressed Concrete Cylinder Pipe*, American Water Works Association Research Foundation (AwwaRF), Report No. 91214, Denver, CO.

San Diego County Water Authority (SDCWA) (1999-2013). "Annual Report," San Diego, CA.

Stine, G., and M. Stift (1998). "Rehabilitation of 183 cm PCCP with Steel Plate Liners." ASCE 1998 Pipelines Division Conference: Pipelines in the Constructed Environment, J. Castronovo and J. Clark, eds., American Society of Civil Engineers, Reston, VA.

The Navy Ring (1997). "Captain Buckley L. Ogden CEC USNR-RET," <http://webspace.webring.com/people/du/um_10854/ogden.html> (March 16, 2014).

Troyan, M., Kenny, M., and B. Fountain (2013). "Pipeline Relining of Large Diameter Prestressed Concrete Cylinder Pipe with Steel Liners." NASTT 2013 No-Dig Show, North American Society for Trenchless Technology, Liverpool, NY.