Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.
# PCCP: Condition Assessment, Repair, and Replacement Strategies

## Abstract (Maximum 200 words)

Prestressed concrete cylinder pipe (PCCP) is used by Reclamation and other agencies for water conveyance, primarily as siphons on non-redundant transmission systems. The goal of this study was to survey the state of the art in PCCP condition assessment, repair and service extension methods, and replacement strategies to provide operators with successful strategies for maintaining their PCCP assets.

## Subject Terms
- Prestressed concrete cylinder pipe
- Condition assessment
- Repair
- Water infrastructure

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**Report Date:** September 2019

**Report Type:** Research

**Dates Covered:** 2017-2019

**Title and Subtitle:** PCCP: Condition Assessment, Repair, and Replacement Strategies

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**Performing Organization Report Number:** 8540-2019-31

**Sponsoring/Monitoring Agency Name(s) and Address(es):**
Research and Development Office  
U.S. Department of the Interior, Bureau of Reclamation  
PO Box 25007, Denver CO 80225-0007

**Sponsoring/Monitor's Acronym(s):**
R&D: Research and Development Office  
BOR/USBR: Bureau of Reclamation  
DOI: Department of the Interior

**Sponsoring/Monitor's Report Number(s):** ST-2019-7108-01

**Distribution / Availability Statement:**
Final report can be downloaded from Reclamation’s website: [https://www.usbr.gov/research/](https://www.usbr.gov/research/)

**Supplementary Notes:**

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- **Security Classification of:**
  - Report: U  
  - Abstract: U  
  - This Page: U

- **Limitation of Abstract U**

- **Number of Pages:**
  - 73

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**Acknowledgements**

The authors are grateful for funding support from the Bureau of Reclamation Science and Technology Program.

The authors would like to acknowledge the following Reclamation employees for their significant contributions to the content of this report:

- Nick Casamatta
- Evan Lindenbach
- Daryl Little
- Rich Markiewicz
- Kylie Pelzer
- Ken Sayer
- Kelsi Whitesell
- Patrick Wright

The authors would like to acknowledge the following for providing data and/or comments to support this report:

- Jim Crowley, Santa Clara Valley Water District
- Nathan Faber, San Diego County Water Authority
- Jim Geisbush, Central Arizona Project
- Geoff Keller, Reclamation Phoenix Area Office
- Nader Noori, Reclamation Tracy Field Office
- Ed Salazar, Reclamation South-Central California Area Office
- Kelly Vandergon, Westlands Water District

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Acronyms and Abbreviations

1D one-dimensional
2D two-dimensional
AFO acoustic fiber optic
ASTM American Society for Testing and Materials
AWWA America Water Works Association
BIA Bureau of Indian Affairs
CAP Central Arizona Project
CFRP carbon fiber reinforced polymer
CLSM controlled low-strength material / flowable fill / soil-cement slurry
CP cathodic protection
DC direct current
EC embedded cylinder
EM electromagnetic
ERI electrical resistivity imagining
fps feet per second
GACP galvanic anode cathodic protection
GFRP glass-fiber reinforced polymer
ICCP impressed current cathodic protection
IE Impact Echo
lb pound
LC lined cylinder
mV millivolt
µA/ft² micro amps per square foot
NC non-cylinder
x
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>NDT</td>
<td>non-destructive testing</td>
</tr>
<tr>
<td>NIIP</td>
<td>Navajo Indian Irrigation Project</td>
</tr>
<tr>
<td>OSHA</td>
<td>Occupational Safety and Health Administration</td>
</tr>
<tr>
<td>PCCP</td>
<td>prestressed concrete cylinder pipe (in this report, also used to refer to non-cylinder prestressed concrete pipe)</td>
</tr>
<tr>
<td>PPE</td>
<td>personal protective equipment</td>
</tr>
<tr>
<td>psi</td>
<td>pounds per square inch</td>
</tr>
<tr>
<td>Reclamation</td>
<td>Bureau of Reclamation</td>
</tr>
<tr>
<td>SCVWD</td>
<td>Santa Clara Valley Water District</td>
</tr>
<tr>
<td>SIPP</td>
<td>Spray-in-Place Polymeric liner</td>
</tr>
<tr>
<td>SIR</td>
<td>Slab Impulse Response</td>
</tr>
<tr>
<td>USCS</td>
<td>United Soil Classification System</td>
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<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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</table>
Executive Summary

Prestressed concrete cylinder pipe (PCCP) is used by Reclamation and other agencies for water conveyance, primarily as siphons on non-redundant transmission systems. Reclamation specified PCCP from approximately 1960 to 1990. Beginning in 1984 and continuing through 2016, Reclamation has seen instances of both catastrophic failure and extreme deterioration of PCCP installations. Investigations have revealed problems with the PCCP including split, corroded, and broken wires and damaged mortar coating. Unlike many other pipe types, failure of PCCP is typically by sudden rupture of the pipe wall. For this reason, it is important to have well-developed and actionable condition assessment and emergency response plans for PCCP assets, and to know the risk of failure for each installation.

The goal of this study was to survey the state of the art in PCCP condition assessment, repair and service extension methods, and replacement strategies to provide operators with successful strategies for maintaining their PCCP assets. Each section presents techniques broken down into a method overview, the logistics of implementation, and an order-of-magnitude cost projection. This project also compiled Reclamation’s inventory of PCCP into a web-based geospatial database.

Condition assessment is the first line of defense towards preventing a catastrophic failure of PCCP. Knowing the condition of a pipe and the amount of deterioration that a section can accommodate allows for preventative maintenance planning. Depending on site-specific needs and restrictions, some inspection techniques may be better suited than others. This report outlines the following condition assessment techniques: geologic and site evaluation, corrosion potential evaluation, visual inspection, acoustic inspection techniques, electrical continuity testing, electromagnetic inspection, and acoustic fiber optic monitoring.

Even with a thorough condition assessment plan, necessary repairs to sections of PCCP are inevitable. This report outlines commonly used techniques to extend the service life of distressed PCCP including: repair of cracks in the concrete core, interior and exterior joint repair, mortar repair, installation of cathodic protection, wire splicing and tendon wrapping, and repair via a structural liner.

Finally, when pipeline segments have deteriorated beyond repair, pipeline replacement projects must be considered. Proactive planning for replacement allows work to be budgeted and scheduled and is much preferred to costly emergency replacements. Typically, this would occur via individual replacement of distressed pipe sections, but sometimes replacement of an entire alignment becomes necessary. This report outlines the following replacement methods: replacement with PCCP, replacement with steel, and full-length replacements.
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Introduction

The Bureau of Reclamation (Reclamation) owns the title on 44 installations of active prestressed concrete cylinder pipe (PCCP) totaling approximately 80 miles. PCCP is used by Reclamation and other agencies for water conveyance, primarily as siphons on non-redundant transmission systems. Reclamation specified PCCP from approximately 1960 to 1990. Beginning in 1984 and continuing through 2016, Reclamation has seen instances of both catastrophic failure and extreme deterioration of PCCP installations on several projects (see Case Studies). These primarily included failures attributed to compromised mortar coating and subsequent severe corrosion of the prestressing wire.

PCCP can be generalized into three categories: non-cylinder (NC), lined cylinder (LC), and embedded cylinder (EC). All types of PCCP consist of a concrete core with a high tensile strength prestressing wire wrap and a mortar coating. LC- and EC-type contain a steel cylinder on the exterior or embedded within the concrete core, respectively (Figure 1). The steel cylinder found in LC- and EC-type PCCP functions as a water barrier from internal water pressure. One or more layers of prestressing wire provides a uniform compressive pressure around the core that offsets tensile stresses that occur during internal and external loading conditions. The mortar coating is intended to protect the prestressing wires from physical damage and external corrosion.

Investigations have revealed problems with the PCCP including split, corroded, and broken wires, and damaged mortar coating. Several cases of failed or severely distressed PCCP have been documented where loss of prestressing wire was extensive. Unlike many other pipe types, failure is typically a non-ductile, sudden rupture of the pipe wall. For this reason, it is important to have well-developed and actionable condition assessment and emergency response plans for PCCP assets, and to know the risk of failure for each installation.

The goal of this study was to survey the state of the art in PCCP condition assessment, maintenance, and repair and provide operators with detailed, successful strategies for maintaining their PCCP assets. Each section presents techniques broken down into a method...
overview, the logistics of implementation, and a cost projection. Costs are generalized to order-of-magnitude and are compiled from a variety of sources. Assumptions and exclusions (such as excavation, dewatering, or mobilization costs) are stated, but costs are often highly dependent on site-specific factors. Therefore, these estimates should be used only for general comparison between techniques and should not be considered accurate for planning purposes.

This project also compiled Reclamation’s inventory of PCCP (Table I) and supported development of a web-based geospatial viewer.\(^5\)

**Table I. Reclamation-Owned Inventory of Active PCCP**

<table>
<thead>
<tr>
<th>Region</th>
<th>State</th>
<th>Project</th>
<th># PCCP Pipelines</th>
<th>Length (miles)</th>
<th>Construction Year(s)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>AZ</td>
<td>Ak-Chin Indian Water Rights Settlement</td>
<td>3</td>
<td>8.8</td>
<td>1981</td>
</tr>
<tr>
<td>LC</td>
<td>AZ</td>
<td>Central Arizona</td>
<td>20</td>
<td>25.3</td>
<td>1980-1992</td>
</tr>
<tr>
<td>LC</td>
<td>AZ</td>
<td>Salt River</td>
<td>3</td>
<td>5.5</td>
<td>1992</td>
</tr>
<tr>
<td>MP</td>
<td>CA</td>
<td>Central Valley</td>
<td>6</td>
<td>30.4</td>
<td>1986-1987</td>
</tr>
<tr>
<td>MP</td>
<td>CA</td>
<td>Ventura River</td>
<td>3</td>
<td>4.8</td>
<td>1958</td>
</tr>
<tr>
<td>PN</td>
<td>WA</td>
<td>Columbia Basin</td>
<td>1</td>
<td>1.1</td>
<td>1976</td>
</tr>
<tr>
<td>UC</td>
<td>CO</td>
<td>Dolores</td>
<td>7</td>
<td>3.1</td>
<td>1982-1992</td>
</tr>
<tr>
<td>UC</td>
<td>UT</td>
<td>Central Utah</td>
<td>1</td>
<td>0.9</td>
<td>1987</td>
</tr>
</tbody>
</table>

**TOTAL:** 44 80

- Construction Year(s) represents final year of construction, or completion year, for each pipeline.

While condition assessment is a critical component of PCCP asset management, the resulting data cannot be used alone when making decisions about whether to repair or replace distressed pipe. The obtained information should be fed into a risk matrix which considers a variety of physical, operational, and environmental variables. In general terms, a risk matrix involves analysis of these variables to determine the likelihood and consequences of failure. For pipelines, that means looking at the pipe as a system, breaking it down into individual sections, identifying the risk associated with the system overall and each section individually, and taking mitigating actions as needed. Regular inspections and condition assessments are vital to understanding the likelihood of failure. Risk should be continually re-assessed and updated as additional information from condition assessments become available, as well as when changes to the consequences of failure occur, such as population encroachment on the pipeline alignment or downslope of the alignment. Reclamation has developed a document with more detail and guidance specific to risk analysis of PCCP, TM No. OOP-PCCP-8140-RA-2019-1 “Risk Analysis Process for Prestressed Concrete Cylinder Pipe.”\(^6\) The document can be used in combination with the information included in this report to make informed decisions regarding the management of PCCP assets.
Condition Assessment Techniques

There are a variety of inspection techniques available to determine the condition of a PCCP asset.\textsuperscript{7-9} Depending on site-specific needs and restrictions, some inspection techniques may be better suited than others to a given conveyance system. What follows is an overview of available inspection techniques with guidance on when and how each could be used.

The individual technique sections do not address safety issues. However, in all cases when personnel enter a pipe, be it for an inspection or repair, there is inherent risk and special precautions need to be taken to assure that everyone who enters the pipe remains safe. This includes a Job Hazard Analysis to analyze the hazards association with each pipe entry and plan appropriate mitigation. Mitigation may include engineering controls—such as lock-out-tag-out or forced air—emergency response coordination—such as hole monitors and on-site or on-call rescue teams—and personal protective equipment—such as helmets or hard hats and fall protection. Each job should be evaluated for its unique safety requirements and all staff involved should participate in the safety plan.

Geologic and Site Evaluation

\textit{Method Overview}

During a PCCP condition assessment, it is important to gather information about the geologic and site factors which may contribute to preferential deterioration at specific locations. PCCP located in areas with undesirable geologic or environmental features may experience the most severe deterioration along an alignment, as could pipe in proximity to man-made structures. Identifying such areas will allow those sections of PCCP to be prioritized for investigation, potentially identifying problem areas early.

\textit{Inspection Logistics}

A topographic map of the pipeline alignment should be obtained prior to any condition assessment. Small scale maps can be used to target regions of surface water or steep topographic gradients, while large scale maps can be used to further refine specific sites along the pipeline alignment for investigation. In areas where there is a topographic gradient between two surface water sources near the pipeline, there may be near-surface groundwater flow following topography and/or groundwater flowing in the backfill of the pipe trench. This groundwater could lead to accelerated corrosion of prestressing wires or other exposed metalwork.

A geologic map should also be obtained prior to any condition assessment. Geologic maps can be obtained from the United States Geological Survey (USGS) National Geologic Map Database.\textsuperscript{10} Geologic maps with the largest scale should be preferentially obtained, with small scale maps used to correlate features along the entire pipeline alignment. Both surficial and bedrock geologic maps should be used to guide the investigation. Geologic units with potential for high corrosivity warrant increased scrutiny. These units could include shales, claystones, or other acidic, chloride-rich or sulfate-rich soils/formations.

Pipe located in areas of fluctuating groundwater is susceptible to accelerated deterioration. For this reason, it is important to identify areas of phreatophytes—plants with root systems intercepting the water table (e.g. cattails or willows)—which may indicate near-surface
groundwater. Areas near irrigated fields, irrigation ditches, or ponded water, and areas with seasonal surface water fluctuation, e.g. dry or shallow ponds, should be targeted for inspection.

Other areas that should be identified as at-risk for increased potential for corrosion or deterioration of pipe include:

- areas near underground or above ground electrical transmission lines (aerials),
- areas with nearby cathodically protected structures or potential stray current interference,
- areas near faults or other sources of ground movement,
- foreign pipeline crossings, and
- surface drainage paths including washes, man-made drainage structures, and roadways.

**Cost and Schedule**

The geologic and site evaluation will likely require one to two days of office research and another one to two days of site mapping. Additional effort may be required if the area of interest is large, geologically complex, or lacking in background documentation. If drilling is required, time and costs can be expected to increase significantly. The schedule will be driven by personnel availability, site access, and availability of information.

![Relative Cost in USD ($)](image)

**Figure 2.** The cost associated with geologic and site evaluation is related to the engineering charge out rate to make the assessment. Cost does not include mobilization.

**Corrosion Potential Evaluation**

Corrosion is defined as the degradation of a material or its properties due to reaction with its environment. Corrosion of prestressing wires is a leading cause of failure in PCCP. Corrosion of the highly stressed, small diameter wires results in a high percentage loss of cross-sectional area which can lead to failure. Understanding the corrosivity of the environment in which the PCCP asset is situated is a relatively inexpensive step that can be taken to identify areas where corrosion has a higher probability of occurring. Evaluating corrosion potential can also be useful to give context following a failure or in cases where pipe sections are excavated for condition assessment. Corrosivity data can also be used in the design of a cathodic protection (CP) system.

It should be noted that soil conditions can vary widely even in geographically close areas, and each sample or survey represents only a snapshot of the overall soil environment along a pipe alignment. In addition, the soil environment can change seasonally and over time, so it is important not to simply rely on historical measurements, but to periodically update corrosivity
data, especially when major events occurs such as a new wash being formed, a failure, detection of wire breaks, or installation of a CP system.

Laboratory Corrosivity Testing

Method Overview
The purpose of corrosivity testing is to quantify properties of soil that indicate a high probability for adverse reaction with buried structures, such as corrosion of metals or sulfate attack in concrete. Such properties include the concentrations of water-soluble minerals that may be dissolved and transported to the structure during periods of high precipitation. Lab corrosivity testing typically consists of measuring soil resistivity, pH, and concentrations of water-soluble anions, with primary analytes being chloride (Cl\(^{-}\)) and sulfate (SO\(_{4}\)\(^{2-}\)). Corrosivity testing is particularly useful if a site is being excavated and samples can be collected near the pipe.

Inspection Logistics
Soil samples can be collected from drill holes, test pits, or other excavated areas at the approximate burial depth of the pipe. Enough sample should be collected to fill two quart-sized sealable bags, which should be labeled, placed on ice, and sent to a testing laboratory. Testing should be performed within 28 days of sample collection to avoid deterioration. Samples for laboratory Wenner soil box testing of resistivity must maintain the original moisture content for an accurate as-received measurement; if not, only a minimum soil resistivity will be reported. Minimum soil resistivity represents the potential lowest resistivity but may not reflect the actual field conditions due to changes in soil moisture from in-situ conditions. The Wenner soil box measurement can also be performed in the field. In this case, it is important that the soil be tested immediately upon retrieval and not allowed to dry out.

Cost and Schedule
The major cost driver in corrosivity testing is the sample collection; however, samples are often collected when the pipe is excavated for failure analysis or other condition assessment or during the geologic investigations on proposed new pipe alignments. The corrosivity testing suite itself is approximately $100 per sample, so it can be an economical way to get additional data from a pipe site that is already being excavated. For a new pipe alignment, a sample should be collected every 500 feet, with additional samples at key features, such as washes or road crossings. Turnaround time for testing labs typically runs from a few days to two weeks.

Figure 3. The cost for laboratory corrosivity testing on one mile of pipeline, assuming ten to twelve samples per mile and approximately $100 per sample. Costs associated with sample collection or mobilization are not included.
Soil Resistivity Survey

Method Overview
Corrosion is an electrochemical process, and one of the four required components for corrosion to occur is electrolytic ion transfer. In the case of buried pipes, the electrolyte is soil. The lower the resistivity of a soil, the more conductive it is to electrical current, and, thus, the more conducive it is to corrosion of metals that come in contact with it.\textsuperscript{12,13} Soil resistivity is best measured in-situ via a resistivity survey, but soil samples can also be collected for laboratory analysis (see above).

Inspection Logistics
Soil resistivity is simply the resistance of the soil to pass electrical current over a given distance, and measurements can readily be taken in the field. Field measurements are typically collected using a Wenner four electrode array, or the automated version, Direct Current (DC) electrical resistivity imaging (ERI).\textsuperscript{11} ERI is a geophysical technique that can be used to map the electrical resistivity distribution and structure of the subsurface along the pipe alignment. ERI techniques are typically carried out in one-dimensional (1D) sounding or two-dimensional (2D) profiling surveys. ERI surveys can be performed in difficult terrain; it is a non-invasive method with very little surface impact on soils and vegetation. Because of the variability of the soil environment, multiple resistivity surveys are typically performed along an alignment, preferably every 500 feet and at washes or high-moisture areas.

ERI surveys vary from the Wenner soil box method in that they give in-situ resistivity data as a function of depth and can be correlated to the burial depth of the pipe.

Cost and Schedule
A three-person crew is typical for most ERI surveys, and anywhere from five to ten survey lines can usually be acquired in a typical ten-hour field day. Data must then be analyzed and a 1D or 2D inversion generated.

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{cost 그래프.png}
\caption{Cost for soil resistivity survey assuming one mile of pipeline, vehicle accessibility, an ERI survey every 500 feet, and a three-person field crew, excluding mobilization.}
\end{figure}

Potential Surveys

Method Overview
As mentioned above, corrosion is an electrochemical process; for this reason, electrical potential can be used to identify areas where corrosion may be occurring. The pipe-to-soil and cell-to-cell
methods of inspection provide a map of electrical potential where probable areas of active corrosion can be determined along an alignment.\textsuperscript{14, 15} These tests are often conducted in conjunction with soil resistivity surveys, as the soil resistivity can affect the potentials being measured.

**Inspection Logistics**

For a pipe-to-soil potential survey inspection, also called a close interval survey, an electrical connection must be made to the pipe. This can be done via monitoring station or another above-ground appurtenance. A reference electrode and high-impedance voltmeter with data logger are used to measure potential directly above the pipe at fixed intervals along the length. In areas experiencing corrosion—where current is “leaking” from the pipe—a more negative potential is observed. This technique requires electrical continuity for the entire length of the survey area.

For a cell-to-cell potential survey inspection, also called a cell-to-cell close interval survey, no connection to the pipe is needed and electrical continuity of the pipe is not necessary; for this reason, the method is often used on pipelines that are not electrically continuous. One reference electrode is placed directly over the pipe and a second at a fixed distance perpendicular to the pipe. A voltmeter is used to measure the difference between the two reference cells. They are then moved together at fixed intervals along the pipe alignment. The potential difference between the two cells will increase in areas with active corrosion.

These techniques do not require dewatering or access to the pipe interior. Walking or all-terrain vehicle access along the alignment is required.

**Cost and Schedule**

If the terrain accommodates walking the alignment, each of these types of surveys on a one-mile section of pipe can be conducted in a day on-site with a three-person crew. The lateral accuracy in pinpointing corrosion location is typically +/- the burial depth of the pipe.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Cost for a close interval potential survey assuming one mile of pipeline, accessibility on foot, a measurement every five feet, and a three-person field crew, excluding mobilization.}
\end{figure}

**Visual Inspection**

**Method Overview**

Periodic visual inspections from within the pipe can identify obvious areas of concern prior to performing more costly quantitative inspections. Visual observations of note can include cracks, signs of corrosion, concrete staining or delamination, and water leakage. For each observation,
the time, date, and location-specific information should be recorded for later use and comparison. While not a comprehensive evaluation, this method of inspection is a useful starting point to identify areas for further investigation.

**Inspection Logistics**
Visual inspection requires inspector access to the inside of the PCCP asset. This includes dewatering pipes and manned entry safety precautions, as needed. If there is sedimentation build-up, rocks and/or debris, biological fouling, etc., obstructing the view of potential areas of concern, surface preparations may be needed. Surface preparation could be time intensive and costly depending on the amount of build-up, access, and length of pipe. Inspectors are typically documenting signs of damage, such as cracks in the concrete core or leaks at joints, and they would carry recording and photography equipment and handheld tools such as pit gauges or crack comparators. Inspectors may also perform basic sounding of the pipe (see Acoustic Inspection Techniques section).

**Cost and Schedule**
At a minimum, a visual inspection of the pipe will include a two-person inspection crew and a monitor at each end of the pipe or access point. A one-mile length of PCCP would take two to four hours to thoroughly document, plus an hour each for entry and exit.

![Relative Cost in USD ($)](image)

**Figure 6.** Cost for visual inspections of one mile of pipe, excluding dewatering and mobilization costs.

**Acoustic Inspection Techniques**

**Method Overview**
Mechanical sounding is a method of inspection that involves striking the surface of the PCCP asset with a “dead blow” hammer, chain, or similar tool and listening to the response. Depending on access, the inspection can be carried out internally or externally and usually occurs concurrently with visual inspections. Observed differences in acoustic response indicate a local deviation in the material that can occur for several reasons with common causes being delamination or un-grouted areas.

Impact Echo (IE) is a non-destructive testing (NDT) method that can be used for concrete pipe and slab inspections and evaluations.\(^8,9\) The IE test method utilizes a calibrated impact source, such as a hammer with a known-response accelerometer. This impact source is struck against the pipe or slab surface, after ensuring that the surface is relatively clean and not severely pitted. This impact creates acoustic waves (vibrations) in the concrete, predominantly in the ten
to fifty kilohertz band. A calibrated receiver (accelerometer) and data acquisition system are used to record and analyze the resulting reflected and transmitted acoustic waves. Delamination, voids, slab or pipe contacts, or interfaces will all cause some of the acoustic waves to be reflected back to the receiver. These reflections are compared in transit time and frequency response from known good areas to known or suspected poor-condition areas, and their comparison forms the basis for the evaluation. Good-condition concrete will yield relatively uniform reflections. Poor-conditions will cause the transit time to shorten, with more of the high frequencies lost to poor concrete condition. The more that is known about the poor-condition areas, the more that can be derived from the IE test results.

Several commercially-available inspection systems detect leaks and air pockets by means of a free-floating ball equipped with an array of acoustic sensors. The sensors are encased in a robust outer shell to support the ball as it travels down a length of a pipe with the water flow, collecting data along the way. These devices “listen” for changes in the acoustic signal caused by water escaping from the pipe. The devices are tracked via a surface tracking system until they are collected downstream. Subsequent analysis of the sensor data is carried out after retrieval.

**Inspection Logistics**

Access requirements vary depending on acoustic inspection technique. Mechanical sounding and impact/echo inspections require physical access to the interior of a PCCP asset, which requires dewatering. The free-floating device inspections require only entry and exit point access; however, the contractors will require ground access at specified intervals (roughly every mile) above the pipe to install synchronizers that track the sensor’s movement. Mechanical sounding typically requires a trained and experienced individual in order to accurately detect problem areas, although some defects may be apparent to the untrained ear.

**Cost and Schedule**

Cost for acoustic inspections varies by technique, with systematic mechanical sounding falling at the low end at around $5,000 per mile not including the cost for dewatering or mobilization. The free-flowing device inspections cost in the $7,500-30,000 range per mile including the inspection, data analysis, and reporting. Per one-mile inspection, most of these techniques can be accomplished in a single day on-site.

![Figure 7.](image_url)  
**Figure 7.** Cost range per mile for acoustic inspections varies by technique, with mechanical sounding at the low end and the free-flowing device inspection at the high end. Neither of these estimates include mobilization or site preparation.
Electromagnetic Inspection

**Method Overview**
Electromagnetic (EM) inspection techniques offer a means to identify both the location and number of broken prestressing wires in a PCCP asset.\(^8, 9\) In this inspection, alternating current of a given frequency is applied to a wire coil, known as an exciter coil, to induce a current in the prestressing wire. The current in the prestressing wire can then be detected using a separate wire coil, known as a detector coil. Where the prestressing wire is continuous, i.e. does not have breaks, electrical continuity is maintained and the current detected is relatively high. Should there be any breaks in the prestressing wire, the current detected will decrease.\(^20\) Generally, the decrease in current can be used to determine the relative number of broken wires. Due to the presence of bell and spigot joint rings, electromagnetic inspection does not have the ability to detect wire breaks within approximately three feet of each joint. This inspection requires highly specialized equipment and trained personnel which leads to a significantly higher cost for inspection.

EM inspection is typically performed on a scheduled basis, for example every ten years. As the number of detected wire breaks in a given section increases, the frequency of inspections would be increased. Alternately, monitoring technology, such as acoustic fiber optic monitoring, could be installed in the pipe (see Acoustic Fiber Optic Monitoring). A structural analysis can be performed to produce a performance curve showing number of wire breaks versus operating pressure and the conditions that will produce cracking, yield, etc.

**Inspection Logistics**
Measurements can be taken with the pipe in service or dewatered using either free-floating or manned cart inspection tools, respectively (Figure 8). In most instances, contractors will need to be supplied information about the PCCP asset to develop a testing plan and calibration curves for their instruments. This information can include operating characteristics (flow rate, pressure, etc.), drawings that identify features and access points, and any available PCCP construction details (cylinder type, wire diameter, wire class, wire configuration, etc.).

When the electromagnetic inspection is done while the PCCP asset is in service, a water flow rate between one and three feet per second (fps) is required within the pipe for the equipment to adequately measure signals along the pipeline while traveling downstream. In-line valves will also need to be open to allow the equipment to travel through them, or an access point will be required prior to and after the valves to remove and then re-insert the equipment along the pipeline. When the PCCP asset is inspected while dewatered, a path above the invert of the pipe is required to be cleared of debris to allow for the inspection cart to travel down the pipeline without interference.
Figure 8. Photograph of an EM inspection using a push-along cart at the Pleasant Valley Discharge Line in 2019.

Cost and Schedule
Costs for electromagnetic inspections vary based on pipe size, length, access, and necessary safety equipment, etc. The way the work is contracted, i.e. directly with the inspection company or through a prime contractor, will also affect the cost. An EM inspection while the pipeline is out of service (dry inspection) is typically half the cost of an in-service pipeline (wet inspection). Dry inspections cost up to $45,000 per mile including reporting. This does not account for the cost of dewatering the pipe. Wet inspections cost up to $85,000 per mile including reporting; this does not include the cost to depressurize, as necessary, for launch and retrieval of the probe. Neither of these costs consider mobilization, which can double the cost of the contract. Also, neither of these costs account for the structural analysis of the wire break results or risk analysis.

Figure 9. Cost shows the range for dry and wet EM inspections, including reporting, for one mile of pipeline. Cost does not include site preparation or mobilization.
Electrical Continuity Testing

Method Overview
Direct measurement of electrical continuity of prestressing wire is an effective way to verify the existence of broken wires. After excavation and coating removal, electrical probes are placed on adjacent windings of the prestressing wire and electrical continuity is directly verified. The information provided can be useful for verifying electromagnetic inspection results and subsequently re-assessing the likelihood of failure of the pipe section. In cases where false positives or overestimation of wire breaks were reported, service life can be extended based on the updated information.

Inspection Logistics
While the test itself is simple in nature, electrical continuity testing can be costly due to the associated excavation and coating removal costs. Typically, only a small portion of the crest—a roughly two-feet-wide strip—is excavated, and a longitudinal strip of coating six inches wide is removed to expose the prestressing wire (Figure 10). A multimeter can then be used to check continuity between adjacent prestressing wires. In practice, this is only done where previous inspections, such as electromagnetic, have detected discontinuities and often only when there are other reasons to excavate the pipe.

Figure 10. Photograph of a pipe crown with a section of mortar removed for an electrical continuity test of the prestressing wires. Photo taken in 2018 on the Ak-Chin Link pipeline.
**Cost and Schedule**
The main cost associated with electrical continuity testing is for the excavation and backfilling of the pipe crown. Therefore, this assessment is usually only performed for small sections of pipe or where an excavation is already planned. Excavation and backfilling costs are highly dependent on the pipeline diameter, depth of cover, type of soil, etc. Once the pipe is exposed, a two-person team could remove the mortar, test for continuity, and replace the mortar within an eight-hour work day, costing approximately $5,000. Time for the mortar to cure would be required before backfilling.

![Figure 11. Estimation of cost for mortar removal, continuity testing, and mortar repair on a 20-foot long pipe section with a two-person crew. The costs associated with excavation and mobilization are not included.](image)

**Acoustic Fiber Optic Monitoring**

*Method Overview*
Where the condition of a PCCP asset is of concern but still serviceable, or in areas of high consequence, continuous monitoring is an effective way to extend service life and receive early notification of impending problems. By monitoring wire breaks in near-real-time, condition assessment is continually updated and a PCCP asset can remain in service until a pre-defined level of risk has been reached. Continuous monitoring is achieved using acoustic fiber optics (AFO) and a data acquisition system. With AFO, the vibration from a wire break distorts the cable causing a change in reflected light that can be detected. The number of wire break events are logged, and a break rate can be established. Individual pipe segments continue to be monitored until the wire break limit at which they can be safely operated is reached, at which point they are taken out of service for repair or replacement. This approach requires a baseline EM inspection to determine the existing wire breaks at the time of AFO installation and structural analysis for the pipe class and operating conditions for each segment of concern to determine performance curves and safe operating limits.

*Installation Logistics*
AFO installations require entry and exit points for the fiber optics and a location with access to power and high-speed internet to place the data acquisition system. AFO data acquisition (DAQ) systems can collect data from approximately twelve miles in a single direction from the point of entry. Typically, two cables are used—one to listen for breaks and one to locate the break within +/- 1 meter. Often, bundles of four or eight cables are used for redundancy.
AFO can be installed in both a dewatered pipe and a watered pipe. While the installation cost in the wet situation is higher, the total cost to the client is often similar because the costs of dewatering are eliminated.

**Cost and Schedule**

Cost of installation for the AFO cable in a dewatered pipe has been estimated to be $150,000 per mile for systems under four miles in length, excluding mobilization and dewatering costs. In addition, ongoing costs including monthly data monitoring fees of approximately $1,000 per mile and telephone support of $1,000 per year have been reported. The DAQ system can be purchased or leased, and a warranty for the system can also be purchased, both at additional cost.

![Figure 12](image-url)  

Figure 12. Installation cost for one mile of AFO monitoring in a ten-foot diameter pipe is estimated at $150,000 with a DAQ system purchase of $400,000 and annual support fees of approximately $15,000, not including warranty. Mobilization and dewatering costs are not included.

## Repair and Service Extension Methods

The condition assessment techniques outlined in the previous sections are the first line of defense towards preventing a catastrophic failure of PCCP. Knowing the condition of a pipe and the amount of deterioration, e.g. the number of broken wires, that a section can accommodate allows for preventative maintenance planning.

Even with a thorough condition assessment plan, PCCP is not immune to the effects of aging and there will inevitably come a time when it needs to be repaired. This section will outline examples of commonly used techniques to repair and extend the service life of distressed PCCP. Some of the techniques below, such as installation of a cathodic protection system or repairing cracks in the concrete core, can be implemented at any point in a pipe’s lifecycle and used to extend the service life of the pipeline with little disturbance to the pipe itself. Other techniques, such as wire splice or tendon wrapping, are typically performed as a last resort to prevent catastrophic failure and require significant excavation of the effected pipe sections.

### Repair of Cracks in Concrete Core

**Method Overview**

There are numerous repair materials that can utilized for the repair of concrete within the core of the pipe. The type of material used will depend on width and depth of the crack, availability of...
materials, and in-service conditions of the pipe. These materials include site-mixed cement-based grout, prepacked cement-based materials, and epoxy and chemical grout repair materials.

Reclamation’s “Guide to Concrete Repair, Second Edition” provides a guide to the selection of the appropriate repair material to use for a specific repair type, as well as various repair techniques than can be used in conjunction the various repair materials.

Repair Logistics
After repair areas are identified via inspection of the pipe and a repair plan has been prepared, materials can be taken into the pipe and work can begin. Areas in need of repair should be cleaned of loose material, laitance, and any other foreign material and prepared in accordance with the repair material manufacturer’s recommendations. Obtaining a dry surface to place some repair materials against may be difficult. Once repair materials have been placed, material should cure in accordance with manufacturer’s recommendations. This may take several days depending on the humidity within the pipe. Flowing water over repair material that has not been allowed to properly cure may result in the material being washed away and will require repeating repairs.

Cost and Schedule
Cost can vary greatly and depend on the number and type of repairs needed, as well as repair materials used.

Cost and Schedule
Cost can vary greatly and depend on the number and type of repairs needed, as well as repair materials used.

Figure 13. Cost associated with repair of cracks in three adjacent 20-foot-long sections of ten-foot diameter pipe. Costs for mobilization and dewatering are not included.

Interior Joint Repair

Method Overview
As with repairing cracks on the interior of the pipe, there are numerous repair materials that can be utilized for the repair of interior joints. These materials include a site-mixed cement-based grout and prepacked cement-based materials—some epoxies may also be suitable. If the mortar lining of the interior joint is generally in good condition but leakage has been detected, installation of new interior seals is also recommended.

Repair Logistics
Repair of joints that do not require a new seal is similar to the repair of cracks in the concrete core. There are numerous materials that can be used to repair interior joints. Reclamation’s “Guide to Concrete Repair, Second Edition” is a good resource for the selection of the
appropriate repair material to use for a specific repair type, as well as various repair techniques than can be used with the various repair materials.\textsuperscript{25}

Damaged concrete should be carefully removed from around the joint. The entire joint should be checked for damaged or loose concrete and areas identified should be removed. If the metal ring is exposed, all corrosion shall be removed prior to placing repair materials. Feeler gauges should be used to check the rubber gasket. Remaining concrete surfaces should be roughened and all laitance removed. If a bagged product is used, manufacturer’s recommendations for surface preparation should be followed. Site-mixed or bagged materials should be mixed just wet enough to be worked into and around the joint and remain in place. Some form of tamping or compacting the material into place may be required.

Once repair materials have been placed, materials should cure in accordance with manufacturer’s recommendations. Curing may take several days depending on the humidity within the pipe. Flowing water over repair material that has not been allowed to properly cure may result in the material being washed away and will require repeating repairs.

As mentioned earlier, if a joint is in general good condition, but leakage has been identified, an internal pipe seal can be installed. Commercially-available diameters of internal pipe seals currently range from three to eighteen feet. Surface preparation is like that required for mortar and concrete repairs. Joints must be completely clean of all deposits and/or hard-lime scale laminations before internal joint seals are installed. The joint gaps are then completely filled with Portland cement so that the repair material is flush with internal pipe surface.\textsuperscript{26} Additional surface preparation of the joint area must be performed to fill low spots and grind down high spots. The surface of the joint area and at least one inch on either side of the ribbed section of the seal should be smooth. A surface lubricant is applied to help with the fitting of the seal, but it does not contribute to the seal capability. The seal must be accurately positioned and must bridge the joint gap with the test unit in the seal located at either 9 or 3 o’clock position or in accordance to manufacturer’s recommendations. Position two (or more if using extra wide or double wide seals) stainless steel retaining bands in the grooves provided in the seal and expand the seal into position by applying the correct pressure to the retaining bands radially with the ring expander. The pressure from the expander is released, and, after an hour, the seal is expanded a second time to account for any seal relaxation that may have occurred. The seal is then tested to detect any leaks using the test unit and soapy water. Though the seal provides a permanent solution to leaking joint problems, the seal should be included within the standard pipeline inspection activities.

For large diameter pipelines, scaffolding may be required for either type of interior joint repair.

\textbf{Cost and Schedule}

Cost of an interior joint repair depends on the extent of the joint damage and necessity of a new mortar lining and/or a new internal joint seal.
Figure 14. Cost includes one joint repair for a ten-foot diameter pipe, assuming no interior seal repair is required. For each additional joint repaired, add approximately $5,000 per joint. Costs for mobilization and dewatering are not included.

Exterior Joint Repair

**Method Overview**
For an exterior joint repair, a reinforced concrete collar or encasement may be placed around the joint; ready-mix concrete is typically utilized. The collar or encasement must be designed for the intended loadings on the pipeline. Care should be taken to avoid differential loading conditions on the existing and adjacent pipe segments. Concrete collars are typically used for short sections of pipe or joint rehabilitation; concrete encasements can be used for more extensive pipe rehabilitation.

Concrete encasement is similar to a cast-in-place concrete design which uses the existing pipeline as a permanent interior form. This has significant limitations due to required cure times and cost, though it may be a viable option in certain cases.

**Repair Logistics**
Repairs made by reinforced concrete collar or encasement will have similar construction requirements to any structural concrete feature installation.

**Cost and Schedule**
Cost of an exterior joint repair depends on the diameter of the pipeline, depth of cover, and soil material properties.

Figure 15. Cost for one concrete collar or encasement repair for a ten-foot diameter pipe. Costs for mobilization and excavation are not included.
Exterior Mortar Repair

Method Overview
Prestressing wire provides the chief pressure-retaining strength for PCCP. As such, it is a critical component of the structural integrity of PCCP. In order to reduce the potential for corrosion of the prestressing wire, the mortar coating needs to be intact. Cracking in the mortar coating can allow the penetration of water, oxygen, and chlorides through the thin mortar coating which can cause corrosion of the prestressing wire. This will lead to wire breaks and, ultimately, pipe failure.

Areas of damaged mortar can be repaired with a site-mixed stiff mortar or bagged repair product. Minor areas of missing and damaged mortar coating may be repaired with an application of shotcrete. Exposed prestressing wires should be inspected for damage prior to shotcreting. Repair material should have a high pH and low chloride content.

Repair Logistics
Care should be taken during the excavation of the pipe so as not to further damage the mortar coating. Once exposed, the damaged mortar should be removed to sound material with precautions taken so as not to damage the prestressing wire. Mortar should be wet enough to be worked around and completely encapsulate the prestressing wires in the repair mortar. Material should be allowed to cure and should be protected from the elements during curing.

Cost and Schedule
Cost for exterior mortar repair will be driven primarily by the excavation and backfilling of the pipe. In comparison, the repair itself will be a small portion of the repair cost.

Cost for mortar repair in three adjacent 20-foot-long sections of ten-foot diameter pipe. Costs of mobilization and excavation are not included.

Installation of Cathodic Protection

Method Overview
Cathodic protection (CP) systems protect buried or immersed metallic structures from corrosion. They work in conjunction with a protective coating to control corrosion where the coating has defects or been damaged. Galvanic anode cathodic protection (GACP), also called sacrificial anode cathodic protection, uses the natural potential difference between the steel pipe and zinc or magnesium anode to provide the current required for CP. Impressed current cathodic protection
(ICCP) uses an external power source, such as a transformer rectifier, to supply the current required to polarize a structure.

Prestressing wire is particularly susceptible to corrosion, and its only barrier to the soil environment is a one-inch-or-less thickness of spray-applied mortar coating. If the mortar is sound and maintains a high pH, it can provide a passivating environment and reduce corrosion of the wire. However, there are many scenarios in which the mortar can be damaged or deteriorate, and CP will then act as a backup protection mechanism to reduce the rate of corrosion on the prestressing wires.

There are a few important factors when implementing CP on PCCP. First, all sections should be electrically connected. This is inherent for LC pipe and typically accomplished in EC pipe by use of shorting straps under the prestressing wires during manufacture; conductive clips, bars, or bond cables are used to create continuity across pipe joints during installations. Pipe can be retrofitted to be electrically continuous, but this often requires excavation and mortar removal and repair at the joints to add bond cables. It may be more effective, and economical, in cases where there is no electrical continuity to protect only the section with wire breaks or other evidence of corrosion.

Secondly, prestressing wire is susceptible to hydrogen embrittlement if overpolarized. To avoid this phenomenon, the polarized potential on the steel prestressing wire should not be more negative than -1000 millivolt (mV) to a copper/copper sulfate reference electrode. In cases where the wire is known to be particularly susceptible to hydrogen embrittlement, e.g. 8 gauge type III or IV wire or pipe with a history of hydrogen embrittlement, the minimum polarization of 100 mV in the electronegative direction from the native potential (without CP) is preferable. This is the minimum polarization required to ensure adequate protection of the pipe. A rule of thumb is to design for 100 micro amps per square foot (µA/ft²) based on the pipe’s exterior surface area.

**Installation Logistics**

Because of the limit on polarization to prevent hydrogen embrittlement, GACP using zinc anodes is often employed for PCCP due to the low driving potential of zinc compared to mild steel. A typical H-configuration using vertically oriented anodes is shown in Figure 17. This configuration is useful to avoid shielding on large diameter pipes. For diameters of approximately 36 inches or less, a single anode bed on one side of the pipe can be used. It should be noted that attenuation must be accounted for when designing a CP system for long PCCP sections. Discreet anode beds will produce the effect of large polarization near the bed and less polarization at the midway point between beds unless remote earth can be achieved. In some cases, an excessive number of anode beds would be required to protect a pipe sufficiently without over-polarizing certain areas. A buried zinc ribbon along the entire pipe length has been shown to be effective in these cases. ICCP systems can also be used, but care must be taken not to over-polarize the structure.
Installation of the anodes requires trenching, ideally to the springline of the pipe, to lay horizontally-oriented anodes. Alternately, a shallow trench, approximately three feet deep, can be dug for cable and vertical holes augured for anode installation where midline of the vertical anode is at a similar depth to the springline of the pipe. Cable is then laid from each anode individually or on a header back to a test station or junction box. A section of pipe would need to be excavated and mortar removed to make an electrical connection to the pipe. These cables would also be run to the junction box and connected to the anodes via shunts and variable resistors.

**Cost and Schedule**
The most time-consuming and costly portion of adding a cathodic protection system is retrofitting the pipeline for electrical continuity. If a pipe is already continuous, the driving factor becomes the labor to install the anode beds. Assuming a one-mile length of electrically continuous ten-foot diameter PCCP, it is estimated that four anode beds would be needed in the H-configuration (Figure 17) with approximately twelve anodes per bed and each bed located at “remote earth.” A four-person crew, including a backhoe and operator, could typically install one to two anode beds per day. A conservative estimate for the installation of this system would be $75,000 and four days on-site.

**Figure 17.** Typical H-style configuration for a galvanic anode cathodic protection system on a large-diameter PCCP section.
Wire Splicing and Tendon Wrapping

Method Overview
The concrete compressive stress lost from damaged prestressing wires may be restored by either wire splicing or tendon wrapping techniques. The method employed will depend on the condition and extent of damage to prestressing wires and may not be apparent until after excavation of the PCCP asset. Typically, repair areas are broken up into categories, based on the extent of damage, and the appropriate repair methodology is prescribed. The design of this repair should be specific for the case under consideration. Consideration should be given to wire diameter, spacing, pipe diameter, and loadings. Economics may also determine the suitability of either of these repairs or others.

In areas with few broken and corroded prestressing wires, new wires may be spliced in or anchor blocks used to re-establish tension. Using the wire splicing technique, sections of damaged wire are cut out and replaced with new wires that are spliced in using anchor blocks and subsequently tensioned. The anchor blocks are used to hold both the existing prestressing wire and a measured length of new splice wire. In some cases where the length of damaged wire is short, anchor blocks can be used to rejoin adjacent wires without a splice; prestressing wires are cut, placed within an anchor block, and subsequently tensioned. In both instances, the tensioning device manufacturer’s procedure for tensioning and securing anchors is used to tension the wires to a recommended stress. Appendix A shows a drawing of wire splice repairs on the Central Arizona Project (CAP). The pressures used in the CAP repairs represent a tension of 60 percent of the ultimate strength of the wire.

Where there are significant numbers of broken and corroded prestressing wires in a pipe section, compressive stress in the concrete core can be restored by tendons wrapped around the circumference of the PCCP asset and tensioned to a predetermined stress. Excavation below the pipe will be necessary for the passage of these tendons. After wrapping, the tendons are tightened in a similar fashion to wire splices using anchor blocks and a tensioning device. For pipe with multiple layers of prestressing wires, the entire outer layer of wire and mortar coating are removed before wrapping with tendons. Tendon wrap repairs at a CAP siphon and from a separate repair in Tucson, AZ, are shown in Figure 19, Figure 20, and Figure 21.

If tendon repairs are employed, the entire piece from joint to joint should be tendon wrapped. At locations in the pipeline where tendon repairs have been made, EM inspections can no longer be performed because the tendons will interfere with the electrical signal on the prestressing wire.
Figure 19. Photograph of tendon wrapping operations, Centennial Wash Siphon, CAP.

Figure 20. Tendon wrapping operations on a CAP siphon.
Repair Logistics
The damaged area of the PCCP asset will need to be excavated for access. Depending on the size and location of the damage, specialized safety precautions may be required. There are also logistical considerations for each step of the repair process. In addition to conforming to Reclamation’s construction safety standards, contractors will need to furnish, install, maintain and operate necessary equipment to remove surface water and possibly ground water from excavated areas for the duration of the repair work.  

Following excavation, exposed PCCP surfaces will need to be prepared in accordance with Reclamation guidelines for subsequent inspection and concrete repair activities. In addition to cutting out the damaged wires, the surface of the pipe will need to be prepared prior to splicing in the new wires or installing tendons. Depending on the condition of the excavated section, patch repairs with shotcrete may be necessary prior to installation of tendons or wire splices.

Stress calculations will need to be performed to determine spacing, tensioning strength, and tensioning sequence prior to installation. Caution must be taken to ensure tendon size and spacing does not produce concentrated loads on the pipe. Additionally, tensioning will need to account for stress relaxation to achieve the desired final tension. For this reason, wires or tendons are typically tensioned in multiple steps.
After the specified tension is achieved, the tendons or wire splices are then covered with shotcrete to protect the repaired area, a layer of polyethylene film is applied over the shotcrete, and the excavated area is backfilled per Reclamation standard practices.

**Cost**
The primary driver of the cost of wire splicing and tendon wrapping is excavation and backfill of the pipe. For tendon wrap repairs, the estimated cost per single tendon wrap without excavation is $3000-$4000. Depending on the operating pressure, typically two or three tendons are required per foot. The cost per wire splice would be considerably less expensive.

![Figure 22. Cost of installing tendons every six inches for sixty feet (120 tendons over three sections) on ten-foot diameter pipe. Cost does not include excavation or mobilization.](image)

**Repair via Structural Liner**

**Steel Liner**

**Method Overview**
Where exposing the pipe by excavating is not possible due to highway crossings or other conditions, steel liners may be installed inside the PCCP. Depending on the pipe diameter and access conditions, liner sections may be installed in half sections and welded together by means of butt straps. The end sections of the liners need to be attached to the PCCP and the annulus between liners and PCCP filled with grout. The steel liner is typically designed similar to steel pipe, assuming the PCCP provides an excellent bedding for the steel pipe. The steel liner is fully structural and will assume all loading from the PCCP, should the PCCP fail entirely. Hydraulics should be considered when repairing PCCP with an internal steel liner as the inner diameter of the pipe may decrease which increases flow velocities and hydraulic head losses.

**Repair Logistics**
Special over the road hauling permits may be required for large diameter steel sections. Access to the interior of the pipeline and handling equipment is needed to insert and place the steel sections. Bends in the pipeline need to be considered in the lining design. An appropriate grout annulus must be determined, and the steel sections need to be supported during grouting operations. Grout nozzles will be required in the steel sections. Details of attaching the steel liner ends to the existing pipe will need to be developed.
Figure 23 Steel liner installation in Centennial Wash Siphon, CAP.

Cost
The cost for the steel liner includes excavation, section removal for insertion of the liner, installation of the steel liner, welding, grouting, and coating of the steel. Typical costs range from $2000-$5000 per linear foot, depending on pipe diameter and plate thickness, assuming rural excavation.

Figure 24. Approximate cost for steel lining of three consecutive 20-foot-long sections of ten-foot diameter pipe. Mobilization and dewatering are not included.
Carbon Fiber Reinforced Polymer (CFRP) Liner

Method Overview
Where the integrity of a PCCP asset has been severely compromised, another repair option is to line the interior of the section with carbon fiber-reinforced polymeric composite (CFRP). Where pipe diameters permit access, the major advantage to this method of repair is that it restores the load bearing capacity of the PCCP section without the need for excavation. American Water Works Association (AWWA) Standard C305 specifically addresses this method of repair and should be strictly adhered to. Note that in accordance with this standard, severely deformed PCCP assets, as defined within the standard, cannot be repaired by CFRP.

Prior to any repair activities, segments will need to be identified and inspected. Contractors will require data to design an appropriate liner; this will include information about the PCCP asset as well as geotechnical information about the surrounding soil.

For repair with CFRP, the interior surface and joints of the PCCP section must first be prepared to achieve desired adhesion characteristics. The concrete surfaces are prepared by abrasive blasting to a pre-determined surface finish. The joints on both ends of the section require special preparation suitable to the type of joint termination and bond characteristics required. This can include removal of concrete to expose bare steel, which in turn will need to be prepared to appropriate adhesion characteristics. In all cases, correct surface preparation is vital for successful repair.

Prior to installation, fiber-reinforcing sheets must first be impregnated with resin; this is done on-site with a mechanical saturator. Saturation often takes place outside of the PCCP asset, with the sheets then being brought in through manholes.

Figure 25. Fiber reinforcing sheets are pre-impregnated with epoxy resin using a mechanical rolling system (left) and pre-impregnated CFRP sheets are applied to the interior wall of a PCCP asset (right)
Following impregnation, the carbon fiber sheets are installed in layers using a wet lay-up process. Note that any installation in contact with bare steel will require a base layer of glass-fiber reinforced polymeric composite to protect the base material from potential galvanic interactions with carbon fiber. Sheets are aligned, pressed into place, and overlapped as specified by design until thickness is built up to achieve the desired structural characteristics.

Termination at both ends of the repaired section requires the use of epoxy mortar and stainless-steel expansion rings to prevent water leakage between the inner core and liner. A subsequent top coating of epoxy can be added to the entire system to give the liner extra protection from the environment.

**Repair Logistics**
In addition to access to the interior of the PCCP asset, contractors will require a staging area, near the entrance of the pipe, for impregnating fiber sheets with resin. A minimum two-foot diameter entry via manhole is required to accommodate pre-impregnated sheets. Within the PCCP asset, scaffolding may be required to allow workers to apply the sheets in hard-to-reach areas and without walking on the pipe itself.

**Cost and Schedule**
The installation costs for CFRP lining include climate control, surface preparation, and lining installation and typically run $3000-$6500 per linear foot. Notably, CFRP does not require excavation if suitable manned entry is available for contractor use. This typically results in shorter duration of repairs, sometimes as little as several days, and thus decreases the time for a pipe to be dewatered.

![Figure 26](Image)

**Figure 26.** Approximate cost for CFRP lining of three consecutive 20-foot-long sections of ten-foot diameter pipe. Mobilization and dewatering are not included.

**Spray in Place Pipe (SIPP)**

**Method Overview**
Spray-in-place Polymeric (SIPP) lining is a trenchless repair method that becomes attractive when excavating the PCCP asset is not a feasible. SIPP lining can be semi-structural—i.e. AWWA Structural Class II or III linings—and transfer all internal loading to the host pipe but remain intact across small discontinuities, effectively healing cracks in the pipe wall or joint gaps. SIPP linings can also be “fully structural or structurally independent” AWWA Class IV linings. Class IV linings can withstand operating pressures equal to or greater than the host pipe and are often considered to be the equivalent of a full pipe replacement. AWWA Standard
C620 and American Society for Testing and Materials (ASTM) F3182 address these methods of repair.\textsuperscript{32, 33} Many SIPP lining formulations are capable of meeting NSF/ANSI 61 requirements for potable water systems.\textsuperscript{34}

In general, SIPP consists of one or more layers that can be individually designed for the pipe’s intended use. Two-component polymeric systems are used that are designed for rapid curing—typically epoxies, polyureas, polyurethanes, or hybrids. For Class IV structural liners, a rigid layer of impregnated axially- and/or helically-wound carbon fiber reinforcement is often used to achieve the desired hoop strength. Layers can be added or adjusted to achieve the desired structural properties.

Class IV linings are perhaps of most interest for PCCP rehabilitation, and advancements in SIPP lining technology have allowed engineers to develop robotics to spray a replacement pipe within an existing large-diameter host pipe, making this technique particularly attractive. Some companies can change from one diameter pipe to another during placement with the autonomous navigation, with current technologies claiming the capability of lining pipe up to 144-inch diameter.\textsuperscript{35} Robotic application has the potential to limit safety hazards to workers and increase both the production rate and quality of the SIPP linings. However, many practical limitations still exist, such as the ability to traverse pipe bends and slopes and the need for access points that can accommodate the size and reach of the robot.

**Repair Logistics**

In most instances, SIPP linings are individually designed for the specific performance requirements of the PCCP asset. To do so, contractors need to be supplied information about the pipe such as pressure, the average temperature of the pipe and water inside, internal and external loads, soil conditions, flow, overall pipe layout, and access points. Generally, access points must be 24-inches in size to allow for the SIPP lining equipment to enter and exit. Prior to SIPP lining installation, the host pipe should be clear of debris, sediment build-up, and standing water. If the host pipe is damp, most lining formulations can still be applied. Depending on the contractor’s equipment, hundreds to thousands of linear feet of lining could be placed in one continuous run at a pace of one to six feet per minute. The rate of application is dependent on the equipment, diameter of the PCCP asset, and the number of layers needed for structural integrity.

**Cost and Schedule**

Installation cost estimates for the Class IV structural SIPP lining of PCCP were not available at the time of the writing of this report. Like CFRP repairs, SIPP lining does not always require excavation of the pipe, which can decrease both cost and duration of repairs.

**Replacement Methods**

Because PCCP tends to fail catastrophically, there can be little to no warning of an impending failure. In an emergency failure situation, it can be difficult and costly to procure and transport replacement components to the site, especially in the case of the large diameter, custom-manufactured pipe sections. Time lost during repairs can result in customers without water or cropland without irrigation. Therefore, it is prudent to plan and take proactive measures to prepare for a potential failure of a PCCP section.
Pipeline replacement projects must be considered when inspections begin to detect severe deterioration of pipeline segments. Typically, individual replacement of distressed pipe sections will be the most economical and preferred method. When a projection of increased occurrences of repair sections being required becomes apparent, complete alignment replacement may become necessary. Appropriate planning using given data collected during normal maintenance inspections will allow for scheduling and budgeting for these costly projects prior to the need for an emergency repair. Proactive measures for replacement can also include making sure as-built drawings for a pipe are readily available and having spare pipe sections on-hand.

**Soil and Backfill Evaluation**

*Method Overview*

Before repair or replacement of PCCP sections, it is important to gather earthen backfill and pipe bedding materials for appropriate characterization. Materials should be tested for, at a minimum, water content, particle size distribution (gradation), Atterberg limits, Proctor compaction (if cohesive) or minimum and maximum density if non-cohesive, and concrete/metal corrosion potential. In-place density testing should be performed at the base of the PCCP to ensure that replaced materials are of a similar soil type and density.

*Evaluation Logistics*

The excavation should be thoroughly mapped and photographed during trenching. Areas of anomalous seepage, dissimilar soil type/color/density/etc. should be noted and sampled where appropriate. Pocket penetrometer and/or torvane testing can be used, where appropriate based on soil type, to qualitatively estimate in-place strength parameters and quantify variability in relative material strengths. Proper excavation safety measures should be followed per Occupational Safety and Health Administration (OSHA) requirements.

Appropriate in-place density testing techniques should be used based on the maximum particle size encountered during excavation. Density testing should be done at the base of the existing PCCP, if possible, or in an area where a representative field density can be obtained. Reclamation’s Earth Manual provides detailed guidance concerning in-place density testing.

Nuclear density testing should be used with caution when in a trench or near a structure; testing should follow appropriate ASTM standards.

Existing backfill should be collected in 5-gallon buckets or heavy-duty sealable plastic bags (for corrosivity samples) according to the following quantities:

- Gradation:
  - 3-inch maximum particle = 200-pound (lb) minimum and minimum 50 lbs of material passing the #4 sieve
  - 1.5-inch = 100-lb minimum for cohesive or 200-lb minimum for non-cohesive
  - ¾-inch = 100-lb minimum for cohesive or 200-lb minimum for non-cohesive
  - passing the #4 sieve = 50-lb minimum for cohesive or 100-lb minimum for non-cohesive
- Proctor: 50-lb minimum
- Corrosivity: 1-lb minimum
Buckets should be sealed to preserve water content. Obtained soils should be representative of the existing material underlying and abutting the PCCP. Excavated soils should be replaced with similar soils based on the United Soil Classification System (USCS). To limit a “bathtub” effect of perched water, backfill materials should have approximately the same fines content (material passing the number 200 screen) as the existing pipeline backfill. New backfill should be placed at the same water content and density as determined during in-place density testing to reduce the potential for differential settlement. To the best extent possible, the new backfill materials should be placed and compacted using the same methods used for initial construction, including placing bedding or any other materials. Excavated soils should be transmitted to a laboratory for soil and corrosivity testing per appropriate methods.

**Cost and Schedule**
The soil and backfill evaluation will likely require a day or two of field support (collecting soils, in-place density tests, etc.), and additional time for laboratory testing. Additional effort may be required if the soils underlying the pipe are found to be variable, requiring more testing to fully characterize the subsurface conditions. If drilling is required, time and costs can be expected to increase significantly. The schedule will be driven by personnel availability, site access, and availability of the laboratory.

![Figure 27. The cost associated with the field portion of the soil and backfill evaluation is related to the engineering charge out rate; roughly $1000 per day. The costs associated with the laboratory testing depend on the type of material encountered in the field](image)

**Replacement with PCCP Section**

*Method Overview*
When individual sections of PCCP are recommended to be replaced, as opposed to replacement of the entire pipeline, one option for pipe diameters less than twelve feet is to replace the existing distressed PCCP section(s) with new PCCP. Replacement with new PCCP is not recommended for pipe diameters greater than twelve feet, as significant logistical planning is required, especially when transportation of wide and heavy loads may not be possible within state highway limits.

The pipe sections for replacement will need to be identified inside of the pipeline and correlated to the ground surface location for subsequent excavation and removal of the correct sections. Though it may appear obvious, identifying the same pipe section from the ground surface has not always been intuitive but is critical to avoid damaging adjacent segments. Replacement
activities should be completed during a scheduled outage, when possible, to avoid the added cost of an emergency shutdown.

When spare replacement sections of PCCP are available near or on-site, verification of the pipe condition and pipe joints will be required prior to installation. If spare sections of PCCP are not on-hand, new pipe sections can be designed, manufactured, and transported to the project site concurrently with the planning and design efforts for the replacement. Original design drawings, if available, are beneficial in determining pipe characteristics and joint methods for the new sections. If the typical Carnegie-style bell and spigot, gasketed joints can be utilized, the repair time and costs in welding could be significantly reduced.

Before designing and/or replacing the PCCP, accurate length and diameter measurements should be taken. Many pipe sections may not be perfectly round due to pipe deflections, requiring critical special designs to accommodate variations. Repair sections will also have to be treated as “closure” sections with a butt strap and appropriate clearances to allow for the pipe to be inserted into the existing alignment. If multiple contiguous sections are to be removed and replaced, only one closure section is required for connection to the existing pipeline. Consideration should be given as to whether a new manhole access should be provided at the location of the repair.

Removal of existing pipe sections is typically done by saw cutting the deteriorated pipe section. Care must be taken not to damage or disturb the remaining sections of PCCP during the removal process. Once the distressed pipe section is saw cut, the section should be vertically lifted out of the trench. After removal, foundation preparation, pipe bedding, and/or the use of pipe saddles to support the new pipe prior to backfilling will be required. Controlled low-strength material (CLSM) is a common backfill material. Backfill design and compaction must account for the required wall strength to protect PCCP from earth loads. Corrosion protection and electrical continuity with remaining pipe sections must also be considered.

**Replacement Logistics**

Although one pipe segment may fail at a time, it is possible that additional pipe sections will also require replacement due to their condition or proximity to a distressed section. If there is a catastrophic failure at a joint, both pipe sections adjacent to the joint may need replaced.

Because water delivery outage time may be limited, a detailed plan should be in place before repairs begin. Additionally, having a repair plan in place before a sudden failure can greatly reduce outage times during an emergency repair. Some items to be considered before a repair are:

- determine if there are other sources of water available to users,
- pre-emptively design and stockpile standard repair pieces, if possible; alternately, prepare fabrication drawings for new sections, design and manufacture the PCCP sections and connection detail, and prepare designs for corrosion mitigation,
- ensure the design and manufacture of the closure piece of the replacement is flexible and can adapt to out-of-round pipe connections, out-of-line grade and/or alignment,
- locate pipe fabricators capable of fabricating the required sections,
• determine if permits to haul PCCP sections on highways will be required from local jurisdictions,
• determine if the repair work will be done by force account and/or locate contractors that are qualified and can obtain appropriate equipment,
• determine the safety requirements including confined space, lock-out/tag-out, personal protective equipment (PPE), fall protection, etc., and develop a job hazard analysis document in preparation for repair,
• prepare for site control, to include site security and public and media coordination,
• develop a construction plan to include material handling, equipment required, removal and replacement of pipe segments, and site restoration activities,
• determine the availability of qualified welders to perform the closure section field welding,
• ensure the availability of Government inspectors qualified to inspect the work, including the field welds,
• determine if ground water removal will be required,
• verify the condition of PCCP replacement sections prior to installation,
• plan the water up and testing of the pipeline following repairs; operators should water up PCCP slowly so as not to place undue stress on prestressing wires, and
• identify post-construction activities that can be done outside of the period of dewatering.

It should be noted that, in an emergency, replacing pipe segments costs more. Planning for maintenance and rehabilitation is more cost effective, can save time in getting a system operational, and is always preferred over responding to an emergency. Ensure future access is included in the planning—permitting, neighborhood encroachment, etc., could affect the ability to repair or replace the pipeline in the future. Following a replacement, it is recommended to have the removed pipe sections examined. This will provide information on the remaining pipe sections’ condition and design and enable the establishment of a modified maintenance program to improve the care and operation of the remaining pipe system.

**Cost and Schedule**

The costs associated with a planned pipe replacement with PCCP will vary and are greatly dependent on pipe diameter and the outage length required. If a pipe replacement with PCCP occurs during emergency circumstances, the replacement process could triple in cost.

![Figure 28. Approximate cost for replacement of a single 20-foot-long section of ten-foot diameter pipe with a PCCP section. Mobilization and dewatering are not included.](image-url)
Replacement with Steel Section

Method Overview
Much of the discussion above for replacing PCCP sections with new PCCP also applies to replacing PCCP with fabricated steel. Distressed sections of PCCP are located, excavated, and removed. The determination of an appropriate field connection detail is made to suit the existing PCCP and new fabricated steel sections. This could include a steel ring to be shop-welded to the fabricated steel pipe sections and then field-welded to the existing PCCP steel bell or spigot ring. The existing bell and spigot rings may require some cutting and preparation to accept the steel rings. The steel pipe sections may be fabricated as full circles with butt straps attached and welded together in the field. Fabricated steel sections must be sized for the anticipated internal and external loads including handling, deflection, self-weight, water weight, earth cover, traffic load, internal pressure and external pressure from groundwater when the pipe is empty. Steel pipe will need appropriate internal lining, external coating, and cathodic protection. The completed pipe repair will be backfilled with CLSM or other suitable material. Appendix B includes drawings of steel sections fabricated and stored for emergency repairs of a CAP siphon.

Replacement Logistics
Although one pipe segment may fail at a time, it is possible that additional pipe sections will also require replacement due to their condition or proximity to a distressed section. If there is a catastrophic failure at a joint, both pipe sections adjacent to the joint may need replaced.

Because water delivery outage time may be limited, a detailed plan should be in place before repairs begin. Additionally, having a repair plan in place before a sudden failure can greatly reduce outage times during an emergency repair. See the above list under Replacement with PCCP Section for items to be considered before a repair with a steel section.

Following a replacement, it is recommended to examine the removed pipe sections. This provides information on the remaining pipe sections’ condition and design and enables modification of the maintenance program to improve the operation of the remaining pipe system.

Cost and Schedule
The costs associated with replacing a PCCP segment with a steel pipe segment will vary and are dependent on pipe diameter and the outage length required. If a replacement occurs during emergency circumstances, the process could triple in cost.

Figure 29. Approximate cost for replacement of a single 20-foot-long section of ten-foot diameter pipe with a steel section. Mobilization and dewatering are not included.
Full-length Pipeline Replacement

Method Overview
For some PCCP installations, it may make sense to replace the entire pipeline. Cost to repair numerous sections may exceed the cost to replace the entire line. However, there are also factors other than cost to be considered in the decision to replace the entire line. One factor is the condition of the existing pipeline and whether the time to design and construct a replacement pipeline is available. Another factor is whether the lengthy water delivery outage required to remove and replace the existing pipe can be tolerated. If only a short water delivery outage is available, and right-of-way is available, a parallel line could be installed with connections made at the upstream and downstream ends during a scheduled outage.

Several factors go into determining the type of replacement pipe that can be installed including cost, operating requirements, head and cover requirements, and the operating entity’s needs.

Replacement Logistics
Depending upon the hydraulic requirements, operating conditions, limitations in manufacturing, and environmental restrictions, replacing the pipeline in-kind may not be possible. Consideration of different pipe materials or methods of construction may be needed. For large diameter pipelines, pipe materials and construction methods may be limited. Material options to consider for large diameter transmission pipelines are steel, precast concrete, and cast-in-place concrete. Other types may be available, but limitations in pressure and available diameters will restrict applications. In addition, each pipe type has its construction challenges. Steel may require significant on-site welding. Concrete pipe may require significant hauling logistics. Cast-in-place pipe requires specialized formwork and skilled concrete construction crews. Each option should be considered thoroughly prior to settling on a replacement project.

Cost and Schedule
The cost associated with a full-length pipeline replacement is extremely dependent on diameter, pipe type, and length. A feasibility study is recommended to determine accurate costs.

Figure 30. Costs would begin at approximately $10 million per mile for replacement of a ten-foot diameter pipeline.
Case Studies

Jordan Aqueduct—Failure 1984

In August 1984, only one month after the pipeline was placed into service, a 66-inch diameter section of embedded cylinder PCCP ruptured on Reach 3 of the Jordan Aqueduct. Construction on this section of pipe had been completed in 1981 and it received impressed current CP beginning in April 1983. A failure investigation by Reclamation concluded that the prestressing wire used in manufacturing the pipe was defective and likely wrapped on the pipe at stresses exceeding Reclamation specifications. Longitudinal cracking of the prestressing wire was found to be ubiquitous along the pipe, therefore, all 2.3 miles of PCCP on Jordan Aqueduct Reach 3 was repaired with a steel liner before recommissioning.

Central Arizona Project, Hayden-Rhodes Aqueduct Siphons—Distressed 1990

The Hayden-Rhodes Aqueduct Siphons, seven in total, were constructed from 1975 through 1980. Six of the seven were 21-foot diameter PCCP, totaling approximately 6.5 miles, with both EC and non-cylinder installed depending on design pressure. Three of the siphons have internal pressure heads exceeding 125 feet. Corrosion monitoring began in 1987 and by 1990 corrosion was severe enough to warrant excavation studies. At that time, an emergency program was established to develop and implement repair and replacement options.

A thorough Causes and Extent report assigned the majority of the distress observed to categories of damage to the mortar coating and corrosion of the prestressing wire. The principle causes of this damage were: defective prestressing wire, carbonation of the concrete core and mortar coating, incomplete encasement and therefore incomplete passivation of the prestressing wire with cementitious material, and pH concentration corrosion cells.

Many areas of the six 21-foot diameter siphons on the Central Arizona Project were repaired with tendon wraps and wire splices. Two high head siphons (Salt River and Agua Fria River siphons) were replaced with parallel flexible steel pipelines. The downstream end of Salt River siphon was lined due to concerns with disturbing the high embankment fill in which it was constructed. Part of Centennial Wash siphon under Interstate Highway 10 was lined with steel. Three abandoned PCCP siphons were left with their open ends capped. The caps have access doors for entry by personnel for future inspections and study of the pipe.

Santa Clara Conduit—Failure 2015

Santa Clara Conduit experienced failure of a 24-foot long section of PCCP in August 2015 (Figure 31). The 96-inch diameter embedded cylinder pipe had a single wire wrap and 16-gauge cylinder. It was designed by Reclamation and construction was completed in 1985. A 2007 EM inspection found 30 broken wires in the section that failed and frequent reinspection to monitor deterioration was recommended. Staff responding to the 2015 failure found the six feet of soil cover fully disturbed and concrete and mortar from the failed pipe up to 100 feet away. Both Reclamation and Santa Clara Valley Water District (SCVWD) commissioned failure
investigations; results indicated the failure was due to deterioration of the mortar coating that lead to corrosion of the prestressing wire.\textsuperscript{3, 39}

Over the course of four weeks, SCVWD staff replaced the failed section of pipe with steel pipe, added an access manhole, repaired two nearby distressed sections of pipe using a structural CFRP liner, and returned the Santa Clara Conduit to service. Although Reclamation had forethought to bury several repair sections of PCCP at Coyote Pump Station, these were not used in the repair. SCVWD instead chose to utilize one of two 96-inch steel pipe repair kits purchased in 2007 and buried at the Coyote Pump Station. The repair kit consisted of a 7/8-inch thick, 12-foot long mortar-coated steel spool and a similar 12-foot-long manhole section together with butt straps and filler pieces. SCVWD is also installing cathodic protection on the Santa Clara Conduit and Pacheco Conduit.

![Figure 31. Rupture of Santa Clara Conduit in August 2015. Photographs provided by SCVWD.](image)

**Kutz Siphon—Failure 2016**

On the Navajo Indian Irrigation Project (NIIP) in Farmington, New Mexico, two sections of the 17.5-foot diameter PCCP Kutz Siphon failed in May 2016 (Figure 32). This EC pipe, which featured double-wire wrap with a 16-gauge steel cylinder, was designed by Reclamation and installed in 1972; it was subsequently title-transferred to the Bureau of Indian Affairs (BIA). In one section of the pipe, EM inspections had shown an increase from 30 wire breaks in 2003 to 60 breaks in 2010. In 2016, the pipe ruptured and blew concrete up to 200 feet away with debris damaging an overhead powerline. Approximately 75,000 acres of irrigated land were without irrigation service, and water was rationed to priority crops.

Reclamation’s Four Corners Construction Office partnered with the Navajo Nation and the BIA for emergency repair and replacement. The two 20-foot long damaged PCCP sections were removed and four new 10-foot long steel pipe sections were installed in their place. The steel sections were field-welded to each other and attached to the existing PCCP steel bell and spigot joints with welded steel rings. The installation was covered in soil cement, shotcrete and backfilled. Service was restored within 30 days. A galvanic anode cathodic protection system
was subsequently designed and commissioned. Detailed information on the failure, repair, and lessons learned can be found in a paper by Duke.⁴

![Figure 32. Rupture of Kutz Siphon in May 2016.]

**Ak-Chin—Distressed 2018**

The Ak-Chin Link Pipeline serves as the sole irrigation water supply for the eastern 8,000 acres of Ak-Chin Farms. The pipeline was constructed and put into service in 1982 and consists of approximately 5.5 miles of 78-inch diameter PCCP followed by approximately 3.0 miles of 84-inch diameter PCCP. It is a low pressure (average 12-15 pounds per square inch (psi) and maximum 18 psi) gravity-fed system.

In July 2018, an EM condition assessment and structural analysis identified eight pipe sections out of the 1,874 surveyed that had over 100 broken wires per section—exceeding the yield limit of the pipe. Immediate remediation was recommended for those sections. Subsequent unearthing revealed severe cracking in the mortar and concrete core and extensive corrosion of prestressing wire (Figure 33). Based on the location of the cracks in the concrete core and the fact that they span joints, it was concluded that these sections experienced an overburden event after installation, e.g. heavy equipment driving over the pipe, which caused the pipe mortar to crack, allowing moisture and other species access to the prestressing wire. Corrosion of the prestressing wire ensued, causing wire breaks and tensile stresses that resulted in mortar spalling. This type of damage was thought to be isolated to the sections identified to have significant numbers of wire breaks.

Reclamation’s Phoenix Area Office coordinated with Ak-Chin Indian Community and their contractors on a remediation plan for the distressed sections of pipe. The eight sections in poorest condition were excavated and capped with reinforced concrete as a temporary repair. There is a plan in place for electrical continuity testing and CP will potentially be installed on the entire pipeline. Future work may also include a permanent structural lining in distressed sections of the pipe.
PCCP: Condition Assessment, Repair, and Replacement Strategies

Figure 33. Inspection photos of damage to Ak-Chin Link pipelines showing spalled mortar with corroded prestressing wires and a longitudinal crack in the mortar spanning joints.

Conclusions

Prestressed concrete cylinder pipe (PCCP) is used by Reclamation and other agencies for water conveyance, primarily as siphons on non-redundant transmission systems. Because of its tendency to fail catastrophically, it is important to have well-developed and actionable condition assessment, periodic maintenance, and repair plans for PCCP assets. Prioritization of work can be determined by the risk of failure for each installation.

Condition assessment is the first line of defense towards preventing a catastrophic failure of PCCP. Combining inspection results with structural and analysis, a performance curve can be produced showing the number of wire breaks versus operating pressure and the conditions that will produce cracking, yield, etc. After a baseline condition assessment has been established, further inspections can be performed on a scheduled basis as needed, for example every five to ten years. As the number of observed defects or detected wire breaks in a given section increases, the frequency of inspections can be increased; or alternately, monitoring technology, such as acoustic fiber optic monitoring can be used.

Condition assessment results are only useful to PCCP asset managers when followed up with either a plan for subsequent inspections, or an actionable maintenance and repair plan. Proactively planning for necessary inspections, maintenance, and repairs, both from a budgetary perspective and from scheduling perspective, can avoid the consequences demonstrated in the case histories presented.
References

1. AWWA C301-14 (2014), "Prestressed Concrete Pressure Pipe, Steel-Cylinder Type" (Denver, CO: American Water Works Association).


5. "Prestressed Concrete Cylinder Pipe - Asset Inventory Database," Bureau of Reclamation (internal use only), link to viewer.


21  B. McDonald, R. Riggs, A. Conroy, "Using Electrical Continuity Testing to Improve PCCP Inspection Results," Pipelines 2016, (Reston, VA: American Society of Civil Engineers (ASCE), 2016).

22  M. Higgins, P. Paulson, "Fiber Optic Sensors for Acoustic Monitoring of PCCP," Pipeline Division Specialty Conference, (Reston, VA: American Society of Civil Engineers (ASCE), 2006).

23  N.D. Faber, "Costs and Benefits for Pipeline Acoustic Fiber Optic Monitoring," Pipelines 2017, (Reston, VA: American Society of Civil Engineers (ASCE), 2017).


29 NACE SP0100 (2019), "Cathodic Protection to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water or Waste Water Service" (Houston, TX: NACE).


32 AWWA C620-19 (2019), "Spray-In-Place Polymeric Lining for Potable Water Pipelines 4 in. and Larger" (Denver, CO: American Water Works Association).


39 "Lessons Learned from August 2015 Pipe Rupture on Santa Clara Conduit," in File No.: 15-440, Board Agenda Memorandum Item No. 2.1, (Santa Clara Valley Water District, April 15, 2016).
Appendix A – Construction Drawing for Wire Splicing and Tendon Wrapping on Central Arizona Project (CAP) Siphons
**REPAIR NOTES**

1. Measure length of cut off old wire "A-D" in inches.
2. Measure length of exposed wire "A-D" in inches.
3. Cut length of splice wire to "A-D" where
   \[ \text{old wire} = \text{A-D} \div 12 \times 12.60 \times 0.80 \]
   (Example: old wire = 12" \times 12.60 \times 0.80 = 1.00 + 12.00 \]
4. Attach anchors #1 to splice wire by driving wire into anchors with a 2 lb hammer.
5. Drive anchor #1 onto existing wire end "A". Use steel shank between wire & pipe to protect (concrete). Clamp anchors #1 & #2 together with a (100) strap (step 12, 13 or 14).
6. Drive another anchor #2 onto existing wire end "B". Use steel shank between wire & pipe to protect concrete.
7. Pull anchors #1 & #2 at end "B" together with 'T' device until hydraulic bag reaches the PE as shown below. Openings on the wire side, these pressures (nominal), a tension of 0.80 of the ultimate strength of the wire.

8. Follow tensioning device manufacturers procedure for tensioning and securing anchors.
9. Release the hydraulic pressure on the tensioning device and remove bag.

**GENERAL NOTES**

- 1. Required for 1/4" wire.
- 1. Required for 1/8" wire.
- 1. Required for 3/8" wire.

**SCALE:** 1/2
TENSION SPACING

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</tbody>
</table>

Note: For 2-layer wire, 1-1/2" plates when only one layer is required. It can be revised as per code.
Appendix B – Fabrication Drawings for Emergency Repair Sections Currently Stored and Waiting Installation Should They Be Needed
Data Sets that Support the Final Report

- Share Drive folder name and path where data are stored:
  T:\Jobs\DO\NonFeature\Science and Technology\2017-PRG-Critical Review of Prestressed Concrete Cylinder Pipe
- Point of Contact: Jessica Torrey, jtorrey@usbr.gov, 303-445-2376
- Short description of the data: inspection reports, historical drawings, trip reports and photos
- Keywords: prestressed concrete cylinder pipe, PCCP, condition assessment, pipeline repair, pipeline replacement
- Approximate total size of all files: 200M