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CONDITION ASSESSMENT OF PRESTRESSED CONCRETE CYLINDRICAL WATER PIPES

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ABSTRACT

Prestressed Concrete Cylinder Pipe (PCCP) has been used in North America, since World War II, to transmit pressurized drinking water to cities and is also used in wastewater and irrigation systems. PCCP consists of a thin steel cylinder lined with centrifugally cast concrete. The concrete core is prestressed by steel wire helically wrapped around the cylinder. Cement mortar coating is applied around the pipe to protect the wire against corrosion.

Though PCCP is known for its good strength and capacity to resist high internal pressure and external loading, it can suffer from several problems. For example, the interaction of aggressive soils with PCCP deteriorates the mortar coating; this allows for groundwater to reach the steel cylinder and the steel wires inside the pipe and causes their corrosion. Under high internal water pressure, the corroded wires might break, which creates distress in the concrete core that might lead to a catastrophic failure.

Because of PCCP's strategic importance, its high replacement cost and the consequence of its failure, the owners need to maintain PCCP lines and prevent catastrophic failures. The maintenance of PCCP lines is difficult especially when repair/replacement decisions need to be made for buried pipes that the engineer does not know their actual conditions. This has created a high demand for condition assessment methods for PCCP and a few have been developed for PCCP in the last 10 years. This paper discusses the most used non-destructive evaluation and monitoring methods of PCCP, their advantages and their limitations.

OVERVIEW ON PRESTRESSED CONCRETE CYLINDER PIPE (PCCP)

Most North American cities have PCCP lines that they use to convey pressurized drinking water and/or wastewater. PCCP are also used in irrigation systems and power plant cooling systems. PCCP is made to resist high internal pressure and soil load; it can be designed to operate under pressures greater than 2.8 MPa (400 psi) and earth covers in excess of 30 m (100 ft) (Hyprescon, 2008). PCCP is a high value asset: for example, the manufacturing cost alone for the pipe sections required for the construction of one km of 1.35 m diameter PCCP is around $800,000. The total length of PCCP lines in North America is estimated to be 35,000 km (Semanuik and Mergelas, 2006) and the replacement cost is around 50 billion dollars (Mergelas et al., 2002). Currently, PCCP is used worldwide. The world's largest PCCP line is in Libya; it was constructed in 1984, and it includes almost 4,000 km of 4 m diameter pipes that transmit around 6 million cubic meters of water daily.

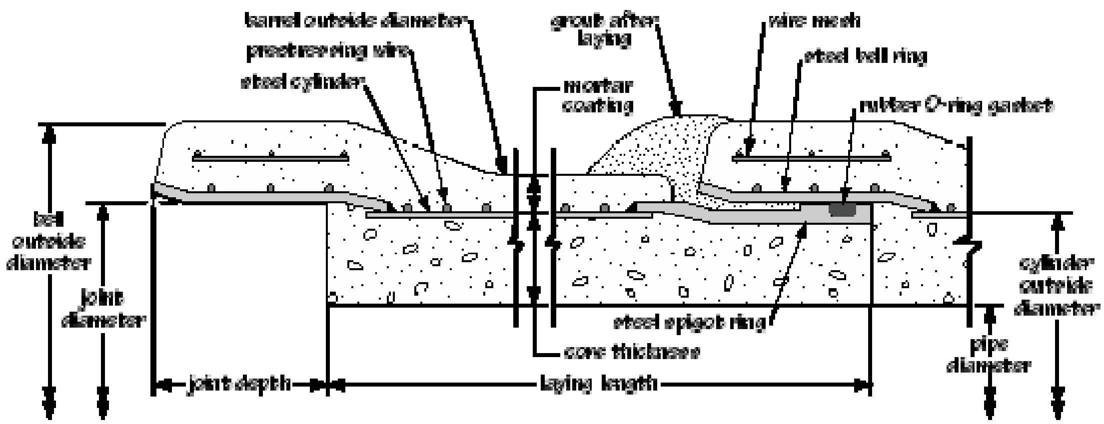

Figure 1.: Price Brothers Company - longitudinal section of AWWA C-301 (LCP)

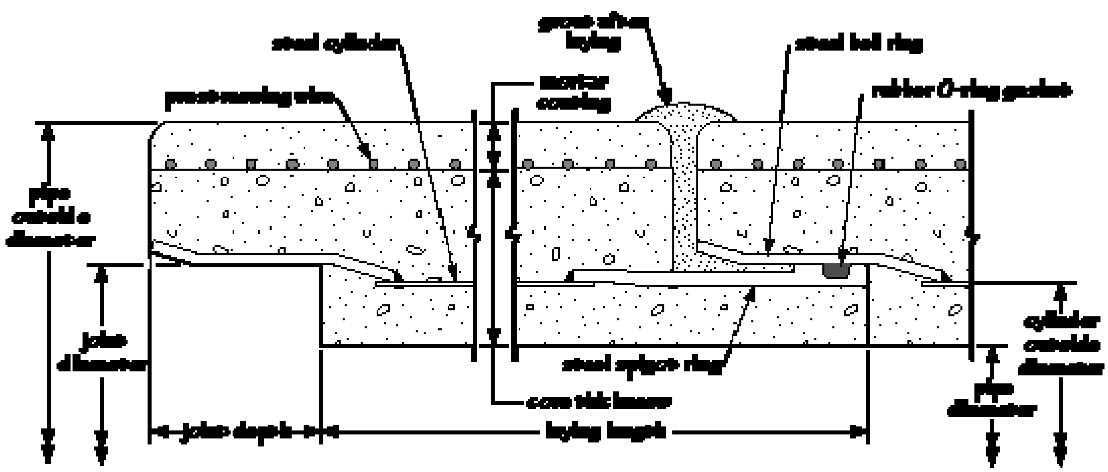

Figure 2: Price Brothers Company - longitudinal section of AWWA C-301 (ECP)

Since its introduction during World War II, the use of PCCP has increased due to the following advantages:

- PCCP is a high strength pipe that can be customized to fit different applications.
- It is easy to install thanks to its bell and spigot joints.
- It does not require interior coating.
- The external mortar coating of PCCP prevents better external corrosion compared to welded steel pipe and ductile iron pipe.

There are two types of PCCP, described by AWWA C-301 standard: Lined-Cylinder Pipe (LCP) and Embedded-Cylinder Pipe (ECP). LCP is designed for diameters generally between 0.4 m and 1.5 m. It consists of centrifugally cast concrete inside a thin steel cylinder. ECP is designed for larger diameters, between 1 m and 3.6 m. The steel cylinder in ECP type is embedded in a concrete core by vertical casting of concrete. In both types, the concrete core is cured and a steel wire is helically wrapped around the cylinder. A cement mortar coating is sprayed around the pipe to protect the wire against corrosion.

Most PCCP mains are designed to reach a minimum service life of 50 years. Longer service life can be reached depending on the operating conditions of the pipe; for example, water mains that operate under high pressure tend to break more frequently than sewer mains.

PCCP FAILURE

PCCP suffers from a variety of problems that can significantly affect its integrity and might lead to failure. PCCP problems can be listed as follows:

- Deterioration of the mortar coating: aggressive agents such as sulfate ions and acidic groundwater that exist in soil surrounding PCCP attack the mortar coating of the pipe and cause its deterioration (cracks, spalling). This puts ground water and oxygen in direct contact with the prestressing wires and/or the steel cylinder and leads to their corrosion. Chloride ions resulting from deicing salt used on roads during winter infiltrates into the soil and penetrate through the mortar coating causing corrosion of the prestressing wires and the steel cylinder. The corrosion products formed at the steel surface induce expansion forces between the mortar coating and the wires and/or the steel cylinder, which results in the delamination and spalling of the concrete coating.
- Wire break: Prestressing wires have the role of compressing the concrete core to increase its strength and make it strong enough to resist the high internal water

pressure. A wire under corrosion progressively loses its cross sectional area. At an advanced stage of corrosion, the wire loses a significant portion of its cross section and breaks when the remaining effective section reaches its maximum capacity to resist tension forces. Hydrogen embrittlement is another cause of wire break. A single wire break is not a problem as the remaining wires can still compress the core. The more that adjacent wires break, the less the core is compressed and the greater the risk of pipe failure becomes.

- Deterioration of the steel cylinder: It is important to note that the steel cylinder is not designed to play any structural role in PCCP; it is only used as a watertight membrane. The steel cylinder can start corrosion when groundwater and chloride ions reach it. This is typically associated with the corrosion of prestressing wires and the deterioration of the protective mortar coating.
- Deterioration of the concrete core: when the number of broken wires is significant, relaxation occurs in the concrete core and longitudinal cracks appear at the inner surface of the pipe. This kind of crack indicates that the pipe is at high risk to fail and is near rupture. Since preventing catastrophic failure of PCCP is the main objective in maintenance planning, the owners should act before the deterioration of the concrete core happens.
- Joint misalignment and differential settlement: installation errors due to lack of quality control during construction of PCCP lines might result in joint misalignment. Under external load, and changes of soil properties along the pipe, differential settlement of the pipe sections might occur causing joint break. The concrete grout placed at the joint might deteriorate due to chemical attacks in aggressive soils and causes the corrosion of the steel at the joint.

PCCP failure is often catastrophic because it occurs with no leak that can serve as an alarm by being visually detected at the surface, and would allow for rapid intervention to repair the pipe and therefore prevent the failure. Failing PCCP ruptures suddenly, causing serious damage to nearby property and, sometimes, human injury. The failure consequences include high costs related to service shut down of the pipe, traffic shut down of the road if the pipe is located under an urban road, soil excavation, pavement reconstruction, etc. PCCP failure is always associated with lack in maintenance operations due to under estimating the condition of the pipe and thus its priority to be repaired. There is no available standard method yet that utilities can follow to make decisions on prioritizing interventions to repair PCCP mains. Some PCCP owners have developed their own maintenance strategies that rely on historical recorded data and some specific conditions associated with their PCCP lines. Recent research studies have proposed analytical (Kleiner, 2005) and finite element (Zarghamee et al., 2003) models that help to set repair/replacement priorities based on the failure risk analysis. However, these models require good data that represent the actual conditions of the pipe. Such data are not always available due to the fact that PCCP is generally inaccessible for inspection. Even when arrangements can be made to access the pipe, either by excavating the soil or taking the pipe out of service to allow man entry inside the pipe, the data might not be very helpful as they are often drawn from visual inspection, which does not allow for reliable assessment of the pipe condition. Existing non-destructive methods and monitoring systems can provide better data. However, they are not always affordable due to budget limitations and to the fact that they require taking the pipe out of service, which is a big concern for most pipe owners.

NON-DESTRUCTIVE METHODS FOR EVALUATION AND MONITORING OF PCCP

Because of PCCP's strategic importance, its high replacement cost and the consequence of its failure, the owners need to maintain PCCP lines and prevent catastrophic failures. The maintenance of PCCP lines is difficult, especially when repair/replacement decisions need to be made for the pipes that their actual conditions are not known. Therefore, condition assessment methods are becoming an urgent need and the demand for non-destructive technologies that can help prioritize repair work and make repair/replacement decisions is increasing. Not many methods exist currently for non-destructive evaluation of PCCP, and most advances were developed in the last 10 years. The most used non-destructive evaluation and monitoring methods for PCCP, their advantages and their limitations are presented in the following.

Visual and Hammer Sounding Inspection

Visual and hammer sounding inspection is the basic, the first and the most used method to inspect PCCP. It is conducted either from outside an uncovered in-service pipe, or from inside a pipe taken out of service to allow man entry. This method consists of recording visible deterioration and hollow sounds (generated by hammer or rod strike on the concrete surface) along the pipe. External observations include: degradation of the mortar coating, longitudinal and/or circumferential cracks in the mortar coating, spalling, broken wires, corroded wires, corroded steel cylinder, rust stains, longitudinal cracks, circumferential cracks, and efflorescence. Less symptoms can be observed on the internal surface of the pipe due to the degradation mode of PCCP, which starts from the outside mortar coating and reaches the inside core at advanced stages of pipe distress only. Internal observations include longitudinal and circumferential cracks in the concrete core, stains, construction and previous repair errors and joint problems. The hammer sounding aims to detect a "hollow sound" area, which is often associated with detachment of the steel cylinder from the concrete core and delamination of the outside mortar coating. The major advantage of the visual and hammer sounding inspection method is its simplicity, including: no sophisticated and expensive tools are needed (only the inspector's eye and a steel hammer or rod); rapid survey rates, which allows inspection of long distances in a relatively short span of time; it is easy to conduct with one or two persons; and it does not require highly experienced inspectors. However, the application of the visual and sounding inspection method in PCCP has shown limitations due to the fact that PCCP is buried in most cases, which prevent the access to the external surface, where most problems first occur. Another way to apply visual and sounding inspection on PCCP is by dewatering the pipe and conducting the survey from the inside. However, the inside surface of PCCP does not necessarily show ongoing problems in the pipe. Major decisions should not rely on the visual and sounding method alone, as the method is very limited in its ability to detect the various complicated forms of distress in PCCP (e.g. wire breaks, corrosion, and delamination).

Electromagnetic Methods

There are currently two electromagnetic methods commercially available to inspect PCCP: Remote Field Eddy Current/Transformer Coupling (RFEC/TC) and Polar wave (P-wave). Both methods can provide information on the number of broken wires in PCCP. RFEC/TC and P-Wave are PCCP-adapted forms of the remote field eddy current and magnetic flux leakage methods widely used to inspect ferromagnetic oil and gas pipelines. The methods (RFEC/TC and P-Wave) use moving platforms equipped with electromagnetic systems to conduct the survey from inside dewatered PCCP with an approximate survey rate of 1 m/s. The electromagnetic system consists of an emitter, which generates an electromagnetic field, and a receiver to catch the electromagnetic energy transmitted through the steel wires. The recorded signal at the receiver shows distortion when a wire is broken, which allows for estimating the number of broken wires in the inspected pipe. Published applications of electromagnetic methods showed a good degree of satisfaction, thanks to the quantitative nature of the results (number of broken wires), which allows for calculating the actual pipe capacity and thus estimating the risk of failure and setting its priority to be repaired or replaced. However, comparison with forensic investigations showed that, while the electromagnetic methods provided accurate estimation of broken wires in some pipe segments, other results were found to underestimate or overestimate more than two times the number of broken wires in PCCP (Donaldson et al., 2006; Mergelas and Kong, 2001). Higher accuracy of results requires conducting calibration tests on test pipe sections to better understand the electromagnetic signal and determine the number of broken wires. The calibration tests are needed to be done on a section of the inspected pipeline and require extracting pipe sections, cutting wires and calibrating the method relative to the pipe diameter, the number of broken wires and their location in the pipe. The calibration procedure is time consuming and not always allowed by the pipe owner. RFEC/TC and P-Wave electromagnetic methods present a blind spot of approximately 0.3 m near the joints, and the number of broken wires in multiple break regions is difficult to determine (Mergelas and Kong, 2001). Other limitations exist, such as the methods are not yet able to determine the circumferential location of the wire break, corroded wires and multilayer wraps cannot be detected, no information on the concrete conditions is provided and, finally, the data analysis needs to be carried out by an experienced person. Even with these drawbacks, RFEC/TC and P-Wave methods are still considered to be good tools, and are often recommended for rapid inspection of PCCP and overall ranking of the pipe conditions.

Acoustic Monitoring

Acoustic monitoring is used to monitor the condition of in-service PCCP by continuously recording the sound transmitted through the pipe, which is generated from ongoing "loud" deterioration occurring in the pipe, such as wire breaks. The system consists of installing acoustic sensors along the pipe that continuously record the sound. The available commercialised systems monitor the pipe using: a) accelerometers placed on external accessible surfaces of the pipe, such as manholes and valve chambers, b) hydrophone arrays inserted inside the pipe through a manhole, or c) continuous fiber optic sensors deployed manually inside the pipe. Following an acoustic event, the recorded signals are analysed and compared to an existing database to determine the nature of the event (e.g. wire break or other event). If a wire break is detected, its location can be easily determined using the travel time of the sound recorded at two or three stations.

A large number of cities that have experienced PCCP problems have subsequently implemented acoustic monitoring for a certain period of time (3 or 6 months) to identify PCCP sections that have higher risk to fail in the future. When used in conjunction with other condition assessment methods, such as electromagnetic methods, soil resistivity, potential survey and chemical analysis of samples retrieved from the pipe, results of acoustic monitoring become easier to interpret and condition ratings are more precise. The use of only acoustic monitoring to determine PCCP conditions is not that accurate for two reasons: a) the capability of the acoustic monitoring is restricted to detect ongoing wire breaks and cannot detect already broken wires, and b) the monitoring period is short compared to the age span of the pipe and does not allow recording events that happen outside the monitoring period (some pipes present problems at only certain seasons, depending on their specific soil conditions and external loading).

Impact Echo Method

Impact Echo is a non-destructive method widely used in concrete structures to determine concrete thickness and detect delamination. Impact Echo uses a) an impact source such as hammer or steel ball to generate sound waves at the surface of concrete, and b) accelerometer positioned near the source to record the echo reflected on internal interfaces such as delamination or that reflected on the other side of the tested concrete. The method involves a simple signal processing technique that provides results in the real time of the test: thickness, depth of delamination, and sound velocity inside the concrete, which is an indicator of the concrete quality.

Impact Echo was used to inspect dewatered PCCP from inside the pipe. Even though the method was successfully applied to concrete structures, its use to inspect PCCP presented some difficulties:

- The method yields to indications, which are not necessarily related to features that reduce structural integrity of the pipe (Dingus et al., 2002).
- It is difficult to detect problems in the mortar coating of the pipe (Dingus et al., 2002).
- The method is not yet automated to inspect the entire pipe surface with a reasonable survey speed.

Sonic/Ultrasonic Method

This method, specific for PCCP inspection, generates sonic waves (using an impact source) and/or ultrasonic waves (using an ultrasonic pulser) in the pipe wall and analyses their recorded time and frequency characteristics (using an array of sensors placed near the source) to determine the possibility of wire break. The test can be conducted either from inside dewatered pipe or from outside in-service pipe. Velocity and frequency of pipe resonance are measured to determine the concrete quality and detect delamination and/or cracks. Even though the Sonic/Ultrasonic method provides information on concrete, its accuracy in detecting broken wires is not yet clear. The method appears to be good for testing selected uncovered PCCP sections from the outside. However, inspection of long distances from inside the pipe is time consuming due to the non-automation of the survey process.

CONCLUSIONS

Based on the current review of the available methods for condition assessment of PCCP, it is concluded that:

- To prevent catastrophic failures of PCCP, regular inspections are required. Non-destructive methods for PCCP are helpful and available on the market.

- RFEC/TC and P-Wave appear to be practical for PCCP inspection as they allow for identification of problematic pipes with a reasonable survey rate. However, the results might underestimate or overestimate the number of broken wires in PCCP, and thus it is recommended to use additional methods to better determine the real conditions of the pipe.
- Further developments are needed to create new non-destructive testing tools that can inspect PCCP without taking the pipe out of service, and which can be used more comprehensively to evaluate the condition of the concrete and the steel cylinder.

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