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OBJECTIVES:
This Manual is intended to be a user-friendly Best Practices Manual for condition assessment, monitoring, and remaining service life/failure margin analysis of prestressed concrete cylinder pipe (PCCP). The Manual provides an overview of available technologies, summarizes best current practices for condition-assessment and prediction of remaining service life, and provides assistance to utilities in identifying the most appropriate technologies for their system. It is also intended to provide an understanding of the limits of applicability of the available technologies and trends in future developments in PCCP condition assessment and determination of failure margin and repair priority. The manual is based on a literature review and the results of questionnaires distributed to, and a follow up workshop of, water utilities, service providers, and consultants.

BACKGROUND:
PCCP lines have been used for water transmission for more than 65 years and represent the backbone of many water systems in the United States, Mexico, Canada, and overseas. PCCP was the pipe of choice for large diameter transmission lines throughout the United States in the years between the mid-1960s and the end of the 1980s. By then nearly 100 million feet of pipe had been installed throughout the United States and Canada (Clift 1991). A few ruptures of PCCP in the early 1990s created a sudden apprehension about the use of the pipe. The failures of PCCP were in general catastrophic due to their large diameter and high internal pressure.

A recent study sponsored by WaterRF indicates that nearly 19,000 mi or about 5 million pipe pieces had been produced in the United States between 1940 and 2006 (WaterRF Report 91214). Results of electromagnetic inspection of about 175,962 pipes (nearly 700 mi or about 3.5% of all installed PCCP) in North America indicated 6,431 distressed pipes with one or more broken wires (Semanuik and Mergelas 2006), corresponding to 3.7% of the total number of pipes inspected. This indicates that on the average about 96.3% of inspected pipes do not have any broken wires. The prevalence of distress in any given pipeline may differ significantly from this average rate based on a number of factors including pipe design, manufacture, aggressiveness of the environment to PCCP, and frequency and magnitude of actual transient pressure events and loads experienced by the pipeline.
Distressed pipes having a small number of broken wires were providing service at the time of inspection, and would likely continue to deliver service with a risk of rupture that may initially be very low and gradually increase with time, leading ultimately to rupture. In general, distressed pipes may continue to provide service at very low risk of rupture for years or decades after the onset of distress. Based on the experience of the authors, the number of distressed pipes with high risk of failure is typically about an order of magnitude less than the number of distressed pipes. For this reason, the goal of the condition assessment process is to identify those distressed pipes with unacceptably high risk of failure and repair or replace them before they rupture, thus maintaining the desired pipeline reliability.

**APPROACH:**
The method of approach included the following:

- Perform a literature review of published papers on PCCP condition assessment, performance monitoring, and service life estimation/failure margin analysis.
- Perform an industry survey through a questionnaire sent to pipeline operators, inspection companies, and consultants on the current state of PCCP condition assessment, performance monitoring, and determination of failure margin and remaining service life.
- Conduct a workshop to gather and assess utility experiences, utility needs, and utilities’ perception of gaps in knowledge for future research.
- Evaluate the existing condition assessment technologies based on their accuracy in identifying distressed pipe, accuracy in estimating the level and location of distress, and the usefulness of results for rational determination of failure margin and estimation of time to failure.
- Synthesize the gathered data into a best practice guidance manual to assist water utilities in selecting the appropriate condition assessment and monitoring technologies, frequency of inspection and monitoring, and appropriate methods for maintaining a failure margin that ensures acceptable pipeline reliability.
- Identify further research needed to improve condition assessment techniques and service life estimates.

**RESULTS/CONCLUSIONS:**

**What Works**

In general, what works is a program of pipeline asset management aimed to maintain the pipeline risk of failure at an acceptable level. It generally includes periodic condition assessment, failure margin analysis, identification of pipe pieces with unacceptable failure risk, and repair or replacement of such pipes.

Selection of pipelines or sections of pipelines for condition assessment should be based on criticality. Criticality accounts for the pipeline likelihood of failure, consequences of failure, and system constraints. Selection of inspection frequency and condition assessment technology is different for low, medium, and high criticality pipelines.
Higher criticality pipelines require more frequent inspection and the use of advanced NDT technologies for locating and predicting the level of distress. The results from inspection using the selected NDT technology must be verified through comparison to the results from another technology or field-verification unless substantial verification of the results has already been made and is available.

Once distressed pipes have been detected and the extent of distress estimated, it is necessary to determine the likelihood of failure, failure risk, and repair priority of the distressed pipes. The method of failure margin analysis used to evaluate the likelihood of failure must be based on a calibrated and verified model and must account for the uncertainties in the results of NDT technologies used for condition assessment. Risk of failure of the pipeline can be reduced in a number of ways, including rehabilitation of individual pipes or pipeline sections with unacceptably high risk of failure, reduction of maximum internal pressure, or cathodic protection of an electrically continuous pipeline.

### What Doesn’t Work

In general, what doesn’t work are not having a proper asset management program or having a program that does not properly account for system constraints and consequences of failure, does not accurately quantify the likelihood of failure, and/or does not prioritize rehabilitation based on failure risk.

The consequences of rupture may include quantifiable cost due to property damage, repair, investigation, water loss, and service interruption and non-quantifiable costs, such as risk of loss of life, loss of public trust, and political fallout that should be accounted for. Ignoring or inadequately accounting for these consequences of rupture results in improper assignment of risk and misallocation of resources.

Use of technologies with unverified accuracy in detecting distressed pipes and in quantifying the level of distress in such pipe can result in data that cannot be used to establish the failure margin of the distressed pipe. Inaccuracy in detection of distressed pipe can be either costly as good pipes are repaired unnecessarily or ineffective as bad pipes go undetected. Similarly, use of technologies with unverified accuracy for determination of failure margin and repair priority can lead to error in determining how close the pipe is to rupture, resulting in either unnecessary repair or failure to prioritize highly distressed pipe for repair, thus increasing the risk of pipeline failure.

With limited resources, asset management by repairing all of the distressed pipe identified by an NDT inspection procedure or replacing a part of the line or an entire line with limited distress comparable to the distress level of the pipelines managed successfully by others does not work. In most cases, PCCP with limited number of wire breaks can safely perform under the design loads and pressures for many years. Replacing a section of pipeline with limited distress and a low-to-moderate risk of failure constitutes an inefficient use of scarce resources in a system that could have been managed at a fraction of cost.
What’s Next

The technologies needed by the utilities for improved condition assessment and pipeline asset management can be categorized into (1) pipeline asset management, (2) design improvements, (3) analysis improvements, and (4) future developments. The research needed for the development of the new technologies requires collaboration and financial support of the utilities. Utilities should pool their resources to fund the needed research to solve the challenging problems ahead.

Pipeline asset management needs include methods to determine pipeline criticality using the existing data and establishment of a utility-specific acceptable level of risk. Design improvements include building robustness into PCCP design to account for future distress. Analysis improvements include the ability to estimate remaining service life without a long history of site-specific data, understanding the uncertainties of the electromagnetic inspection results near the pipe ends and for special pipes, and verification of acoustic monitoring results. Future development needs to include condition assessment technologies for PCCP that distinguish between random wire breaks caused by hydrogen embrittlement and clustered wire breaks caused by corrosion, an accurate method for detecting broken wires on excavated LCP and ECP with shorting strap, ability of fiber optic cable to perform wire break and leak detection simultaneously, detection of joint defects, and other condition assessment technologies.

APPLICATIONS/RECOMMENDATIONS:

Effective pipeline management requires allocating resources to the high risk areas of the pipeline where they are needed and not wasting scarce resources on low risk areas of the pipeline. This Manual can be used by water utilities to develop a program of condition assessment, monitoring, and rehabilitation of their PCCP lines based on pipeline criticality and failure risk. Utilities with existing pipeline management programs can use this Manual to evaluate and improve their current program.

Economic Implications. Allocating scarce resources in a systematic, risk-based manner can lower the cost of pipeline management while reducing the risk of pipeline failure. The cost of properly managing a critical pipeline with distressed pipes is typically significantly less than the costs associated with pipeline failure or overly conservative rehabilitation strategies. The costs of periodic inspection and rehabilitation of pipelines with high failure risk can be spread over time to allow planning and budgeting.

Management Concerns. Understanding the pipeline likelihood of failure, consequences of failure, and system constraints allows operators of pipelines to quantify their exposure and prioritize condition assessment and rehabilitation actions. Understanding the capabilities and limitations of condition assessment, monitoring, and failure margin analysis technologies allows operators to confidently select technologies that satisfy their inspection expectations and system constraints. This Manual provides a pipeline management approach that accounts for system constraints and pipelines’ likelihood of failure and consequences of failure. It also provides descriptions of
technologies—including their primary applications, benefits, limitations, and access requirements.

**Technological Advancements.** Water utilities that currently have pipeline management plans in place can use this manual to evaluate their current plan and the technologies they employ for condition assessment, monitoring, and failure margin analysis. Utilities may opt to select different technologies that are better suited for their system or have more reliable verification results. This Manual identifies areas of future technological development that utilities or other stakeholders might choose to support financially or consider using once the technologies have been developed.

**RESEARCH PARTNER:**
U.S. Environmental Protection Agency