PRESTRESSED CONCRETE CYLINDER PIPE CONDITION ASSESSMENT – WHAT WORKS, WHAT DOESN'T, WHAT'S NEXT

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Abstract

This paper presents a summary of the research performed for Water Research Foundation on the evaluation of condition assessment and remaining service life prediction/failure margin analysis technologies in use for prestressed concrete cylinder pipe (PCCP). The project involved a literature review, an industry survey, and a workshop. The literature review integrated the published experiences with all condition assessment and monitoring technologies. The industry survey included design, distribution, and compilation of responses to a questionnaire sent to water utilities, technology stakeholders, and consultants to document their experiences. The workshop provided a venue to discuss utility experiences and utility needs. The results of the literature review, industry survey, and workshop were used to develop a Best Practices Guidance Manual that identifies a method of prioritizing pipelines for condition assessment; condition assessment, monitoring, and failure margin analysis technologies that are in existence or near deployment; benefits and limitations of existing technologies; gaps in knowledge; what works and what does not work in management of a pipeline; and further research and field work needed to improve condition assessment and pipeline management.

Introduction

The goal of PCCP condition assessment is to identify distressed pipes, analyze their margin to failure, and repair those pipes with unacceptable failure risk, thus keeping the pipeline reliability at an acceptable level. This proactive maintenance approach can result in overall improved pipeline reliability and reduced cost of maintenance and repair. The overall objective of this Water Research Foundation project is to provide utilities with a Best Practices Guidance Manual, referred to hereafter as the Manual, based on the available state-of-the-art condition assessment and failure margin analysis approaches for PCCP lines. The Manual provides operators of PCCP lines with an overview of available PCCP condition assessment and monitoring technologies, summarizes the best current practices for condition assessment and failure margin analysis, and helps operators identify the most-appropriate technologies for their system with the given constraints. The Manual also provides an understanding of the limits of applicability of available technologies and trends and future developments in PCCP condition assessment and determination of failure margin, repair priority, and remaining service life.

The Manual synthesizes utility experiences within North America with technologies for PCCP condition assessment, monitoring, and remaining service life prediction/ failure margin analysis, and identifies needs for future research and development.

The method of approach includes the following:

- Literature review. Review of more than 200 published papers.
- Industry review. Results of a questionnaire that was distributed to sixty-four water utilities, ten service providers, and twenty-three consultants.
- Workshop. A workshop that included seventeen participants from water utilities, consultants, and service providers and discussed and shared utility experiences, needs, and practical technologies.
- Manual. We synthesized the data collected into the Manual.

Literature Review

Literature review identified the history, physical bases, and strengths and weaknesses of the most-widely-used technologies for condition assessment, monitoring, and failure margin analysis. Published example applications of each technology demonstrated the usefulness and limitations of the technologies. Literature review also identified technologies in their developmental stages that may emerge in the future. A brief description of the technologies currently in use by utilities is provided in this paper with significantly more detail and a list of references available in the Manual (Zarghamee et al. [1]).

The condition assessment and monitoring technologies currently in use by utilities are internal visual and sounding inspection, external inspection of the pipe surface, leak detection, electromagnetic inspection, over-the-line corrosion surveys, and acoustic monitoring. Stress-wave analysis has also been used by a few utilities and will not be discussed in this paper for brevity sake.

Literature review indicates the following:

- Internal visual and sounding inspection as a standalone inspection method has been able to identify pipes containing near rupture conditions where the pipe has experienced such a severe loss of prestress that the pipe wall integrity is compromised, but the pressure has not been high enough to cause rupture. The method is not a reliable method for identifying distressed pipes with lower levels of prestress loss.

- External inspection can include visual and sounding inspection, electrical continuity testing of adjacent wire wraps (used to identify wire breaks in ECP without shorting straps or in the final wrap of PCCP with multiple wraps), half-cell potential or linear polarization testing (used to identify corroding wires below the mortar costing), laboratory testing of wire (used to determine the quality of the wire), and petrography and laboratory testing of mortar coating (used to determine the quality and the condition of the mortar coating). The results of external inspection are used to verify NDT inspection results and assess the condition of the prestressing wire and mortar coating to potentially explain the cause of distress.

- Electromagnetic inspection can detect broken prestressing wires in PCCP and their location. The number of broken wires can be estimated from signal distortions. The end result from electromagnetic inspection is to identify distressed pipes and estimate the number and location of broken wires that can be used in remaining service life prediction/failure margin analysis. Detection of distress and prediction of the number of broken wires is known to be relatively accurate away from the pipe ends for LCP and ECP with shoring straps. The accuracy of electromagnetic inspection in identifying distressed pipe deteriorates near the joints, and the accuracy of the predicted level of distress is subject to large uncertainties for ECP without shorting strap and near the joints for all PCCP.

- Over-the-line corrosion and corrosivity surveys are used to detect and locate corrosion in PCCP or to determine corrosivity of the soil and groundwater. Pipe-to-soil potential surveys can be used to identify areas of likely active corrosion in electrically continuous pipelines. Soil resistivity and chemical analysis surveys can be used to evaluate the aggressiveness of the environment to PCCP. Over-the-line surveys do not directly provide information regarding the level of distress on the pipeline; however, the information gathered through such surveys plays an important role in identifying areas along the pipeline with higher likelihood of pipe distress.

- Acoustic monitoring identifies and localizes wire-break events as they occur in a pipeline through the detection of the acoustic waves generated by a wire break. Acoustic monitoring data can provide information on the rate of wire breaks in a pipe and can identifying areas of a pipeline with higher acoustic activity compared to other areas. However, it will not provide information about the condition of the pipe at the time of testing. The fiber optic technology developed for acoustic monitoring provides a distributed sensors system along the length of the pipe and thus has a potential (to be proven in the future) for higher accuracy relative to the array sensor technology.

- Leak detection technologies have identified and located leaks based on acoustic signal of leakage, thermal properties of soil, and ground-penetrating-radar reflection patterns. Acoustic-based leak detection technologies are capable of locating and quantifying leaks, while other technologies are indirect and require further investigation to confirm the presence of leaks. Leak detection as a structural evaluation tool is primarily used in LCP lines, which commonly leak due to corrosion of the steel cylinder prior to rupture. Leak detection in ECP is typically used to identify third-party damage or loss of joint integrity due to improper installation of the bell and spigot or harnessed joints, thrust force, or settlement.

The most-widely-used failure margin analysis methods are the use of the risk curves technology and the use of risk-ranking methods, which includes index systems, finite element models that are not based on experimental verification, and criteria based solely on the predicted number of broken wires. Literature review indicates the following:

- Failure margin analysis using the risk curves technology evaluates the effect of broken prestressing wires on the performance of the pipe and its margin to failure using a model verified by hydrostatic pressure testing of distressed pipes, finite element analysis of distressed pipes to failure, and field inspection of distressed pipes. Repair priorities are assigned to pipes with broken prestressing wires in order to identify pipes with unacceptable margin to failure when subjected to the maximum internal pressure and gravity loads. When the rate of progression of wire breaks can be estimated (see Zarghamee et al. [2]), this rate can be used in conjunction with the failure margin to predict the remaining service life of the pipe.

- Risk ranking identifies individual pipes or sections of pipelines that have high failure risk based on evaluation of parameters that are believed to correlate to pipe distress.

- Results of electromagnetic inspection can be used in failure margin analysis, and the uncertainties in the electromagnetic results must be accounted for.

Developing technologies include the following:

- Methods of detecting of wire breaks in PCCP based on pipe-wall stiffness and inductive scan imaging (an electromagnetic method for detection broken wires from the exterior of an excavated pipe).

- Laser profiling inside of pipelines to map the pipe interior surface and detect irregularities such as spalling, deterioration of inner core, and inside joint mortar loss.

Industry Survey

The industry survey was conducted by sending questionnaires to sixty-four water utilities, twenty-three consultants, and ten service providers. Fifteen utilities, one consultant, and one provider responded. Utilities reported using eighteen different condition assessment technologies, five different monitoring technologies, and seven different methods of remaining service life prediction/failure margin analysis. Each of these technologies could be assigned to one of the technology groups identified by literature review described above.

The predominant condition assessment technologies are electromagnetic inspection, in-line acoustic leak detection, internal visual and sounding inspection, and external visual and sounding inspection.

- Utilities provided results of verification of the predicted number of broken wires for RFTC and P-wave electromagnetic inspection technologies. The actual number of broken wires compared well with RFTC predictions. Limited verification results were also provided for internal visual and sounding, impact echo, Sahara, and Smartball inspections. More verification of condition assessment technologies need to be performed, and the results of verifications need to be published for use by others.

- The cost of electromagnetic inspection varies from about \$12.5k to \$28k per mile, excluding dewatering (if needed). The cost of in-line acoustic leak detection ranges from about \$11k to \$23k per mile. Other leak detection methods, e.g., visual and listening, ground microphones, and correlators, generally have lower costs. Internal visual and sounding inspection generally costs about \$2k to \$3k per mile, excluding dewatering. The cost of dewatering is generally about \$300 to \$500 per mile per inch diameter. The cost of external inspection is about \$10k per pipe, including excavation. These costs can vary widely depending on the length of inspection, pipeline accessibility, and numerous other factors.

- Gaps in condition assessment technology that require more research and development include (1) accuracy of electromagnetic inspection in prediction of distress levels for ECP without shorting strap, (2) accuracy of electromagnetic inspection near the pipe joints and for pipes with thick steel cylinder or multiple wraps, (3) a nondestructive calibration method for electromagnetic inspection, (4) a nondestructive testing method for detecting broken wires on excavated LCP and ECP with shorting straps, (5) a nondestructive testing method to differentiate between wire breaks due to corrosion and embrittlement, and (6) a nondestructive testing method to detect joint corrosion.

The predominant monitoring technologies are acoustic fiber optics, hydrophone arrays, and hydrophone stations.

- The cost of acoustic fiber-optic monitoring varies from about $70k to $170k per mile per year, including installation (except dewatering) and monitoring. Hydrophone arrays generally cost about $70k per mile per year, including installation and monitoring. The cost of hydrophone stations is about $30k per mile per six months, including installation and monitoring.

- Gaps in monitoring technology include the verification of acoustic monitoring results, the ability of acoustic fiber-optic monitoring to detect wire breaks and leaks simultaneously, the high life-cycle cost of acoustic fiber-optic systems, and the need to have a baseline estimate of the number of existing wire breaks prior to the start of monitoring.

The predominant methods of failure margin analysis are use of the risk curves technology, structural analysis using a model that has not been verified experimentally, and use of a specific number of broken wires believed to correlate with failure.

- The cost of using the risk curves technology varies from about $7k to $29k per mile, depending on the inspection length and level of distress. The cost of structural analysis using an unverified model varies from about $5k to $7.5k per pipe design. Minimal costs are associated with evaluation of failure margin using a specific number of broken wires.

- Gaps in failure margin analysis include potential for error due to uncertainties in inspection data, long history of inspection data needed to estimate remaining service life, and a probability of failure model based on measured degradation.

Successful risk mitigation strategies employed by utilities include rehabilitation of distressed pipes by replacement; repair using steel liner or carbon-fiber-reinforced polymer lining, or external repair using post-tensioning strands; cathodic protection; pressure reduction; and a recurring inspection and monitoring program.

Workshop

A workshop was held on 20 October 2010 with representatives from nine utilities, two providers, and two consultants in attendance. Discussions during the workshop identified factors to consider when selecting a pipeline (or section of a pipeline) for condition assessment and failure risk analysis, the need to understand and reduce uncertainties in inspection technologies, and the need to account for these uncertainties in failure margin analysis.

Selection of a pipeline for condition assessment and failure risk analysis should be based on the criticality of the pipeline. Criticality is based on the likelihood of failure, the consequences of failure, and the system constraints. Likelihood of failure should account for the applied internal pressure, applied external loads, levels of distress, and any available results of failure margin analysis. Consequence of failure must account for both quantifiable and nonquantifiable costs, e.g., costs of repair, economic losses, political ramifications, and loss of public confidence. System constraints must account for shutdown time required for inspection, excavation requirements, and required safety precautions.

Uncertainties exist in the results of nondestructive testing (NDT) technologies used for condition assessment of PCCP and in the rate of progression of wire breaks in the future. Understanding these uncertainties is of paramount importance in failure margin analysis, which can be combined with the rate of progression of wire breaks to estimate remaining service life. Uncertainties in the NDT results can be reduced through external inspection of selected distressed pipes to count the number of wire breaks. Results of external inspection can be used to calibrate and revise the NDT results. Uncertainties in the rate of progression of wire breaks can be reduced through analysis of successive sets of inspection results as discussed by Zarghamee et al. [2]. Research is needed to further understand and quantify the uncertainties in condition assessment technologies.

Manual

Information gathered from literature review, questionnaire responses, and workshop discussions was synthesized into a 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. Major sections of the Manual are discussed below.

Risk and Asset Management

The failure risk of a pipeline typically is expressed as the product of the likelihood of failure and the consequence of failure. In general, the initial step in asset management of a pipeline is to determine the failure risk using all available data on the pipeline, its condition, and both quantifiable and nonquantifiable costs associated with pipeline failure. Depending on the risk, condition assessment technologies are selected and resources are allocated as needed. Pipelines with low risk (i.e., low probability of failure and low consequences of failure) require no or very little action. Pipelines with high risk (i.e., high likelihood of failure with medium to high consequence of failure or medium likelihood of failure with high consequence of failure) require condition assessment using advanced NDT technologies. The pipelines with medium risk (the remaining combinations) require judgment on whether there is a need to use more advanced technologies.

The process of condition assessment and selection of appropriate technologies is depicted in Figure 1. Condition assessment begins with evaluation of system constraints, consequences of pipeline failure, and likelihood of pipeline failure. System constraints include the total time the line can be out of service, time required for condition assessment work inside the pipeline, and access costs. Consequences of failure include life safety, property damage, environmental impacts, service interruption, public trust, and political cost, some of which are not quantifiable in dollars. The result of this assessment is categorization of the pipeline as one with low, medium, or high consequence of failure. Likelihood of failure must be evaluated in the circumferential and longitudinal directions and may include data related to past pipeline performance, pipe design, construction, operation, inspection results, applied loads, and any results of failure margin analyses.

Pipeline criticality is determined based on likelihood and consequence of failure (risk of failure) and system constraints. If the pipeline is critical, advanced NDT technologies such as electromagnetic inspection and acoustic monitoring will be required for locating and predicting the level of distress, which is used to reevaluate the failure risk and prioritize repairs. The rehabilitation of the pipeline, if needed, can be either in the form of repair or replacement of the individual distressed pipe or in the form of replacement of one or more sections of the pipeline that shows high rate of distress and high likelihood of failure. The determination of individual pipe repair or replacement of a highly distressed section of the pipeline must be based on the economic and structural evaluation of different rehabilitation alternatives.

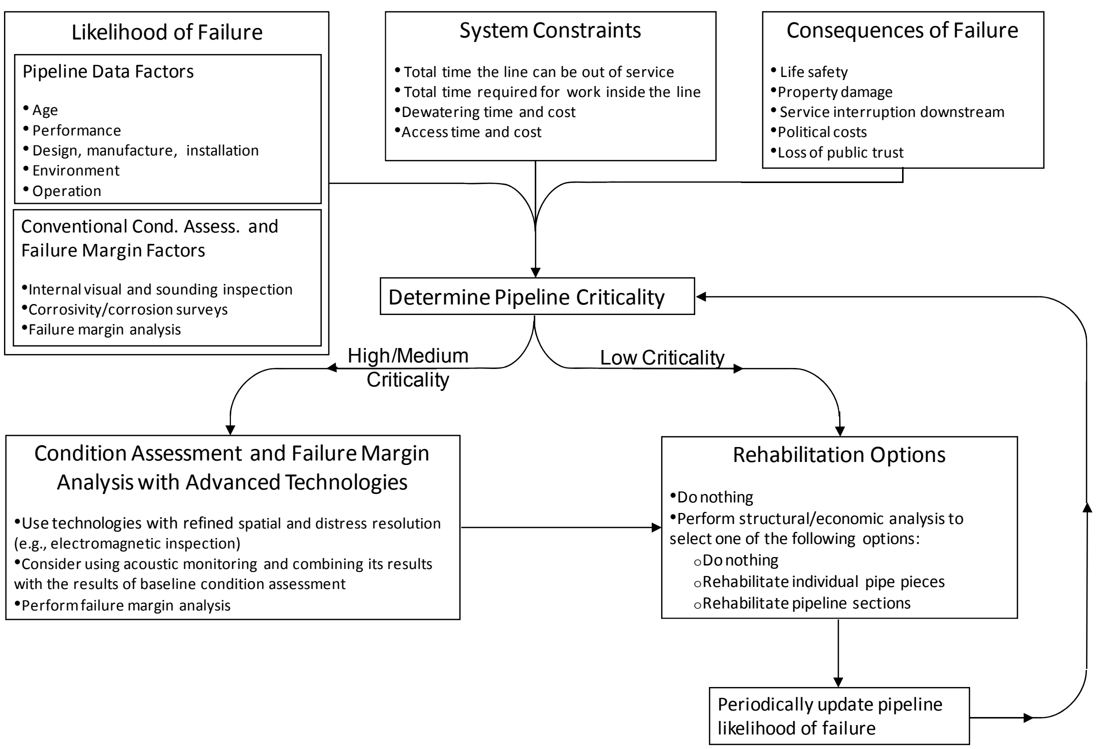

Figure 1. Pipeline selection process and condition assessment approach.

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 inspection, failure risk analysis to identify pipes with unacceptable failure risk, and repair or replacement of such pipes.

Inspection

Selection of a pipeline or section of a pipeline system for inspection should be based on the criticality of the pipeline as determined by evaluation of system constraints, consequences of failure, and likelihood of failure. Selection of an inspection technology should be based on the criticality of the pipeline, the cost and accuracy of the technology, and the applicability of the inspection results to evaluation of pipeline failure margin. Advanced NDT technologies generally have higher cost, but their results also generally have greater accuracy and are directly useful in failure margin analysis. The frequency of condition assessment also depends on pipeline criticality and might range from once every three years for high-criticality pipelines to once every ten years for low-criticality pipelines.

Failure Risk Analysis

The results of inspection may be used to evaluate the failure margin of distressed pipes. The likelihood of pipe failure, say as determined by failure margin analysis, is then combined with the consequence of pipe failure to determine the risk of failure. Uncertainties in the NDT results exist and are related to limitations of the NDT technology and the properties of the pipe, such as no shorting strap or thick steel cylinder. The uncertainty in the NDT results must be accounted for in failure margin analysis, and ultimately in risk analysis, and can be reduced by field verification.

Achieving and Maintaining an Acceptable Level of Risk

Pipelines determined to be at an acceptable risk of failure should be monitored for long-term reliable performance through periodic inspections and reevaluation of failure risk based on the latest inspection data. The risk of failure of a high-risk pipeline can be reduced in several ways including pressure control, spot repair of individual high-risk pipes, rehabilitation of pipeline sections with a high rate of occurrence of distressed pipes, or cathodic protection of an electrically continuous pipeline. Repair/rehabilitation methods include replacement of individual or sections of pipeline; lining a section of pipeline with steel; slip-lining with smaller-diameter steel, HDPE, or HOBAS pipe; internal CFRP strengthening; and external post-tensioning. The evaluation to determine whether spot repair should be used or sections rehabilitated should be based on a hydraulic/structural/economic analysis that compares the current cost of rehabilitation of a section with the present value of the spot repair performed on pipes currently with high risk of failure and those pipes whose risk of failure becomes high in the future.

<u>What Does Not Work?</u>

Concepts that do not work include improper consideration of consequences of pipeline failure, use of technologies with unverified accuracy for condition assessment and failure margin analysis, and overkill in rehabilitation.

Improper Consideration of Consequences of Rupture

Rupture of a large-diameter PCCP, due to its large size and high pressures in the line, releases a large volume of water under pressure, which has an immense destructive power. The destructive power of the released water drives the total cost of rupture up. The consequences of rupture may include quantifiable costs, such as property damage, repair cost, failure investigation expenses, and costs of water lost and of service interruption downstream of the failure point, and nonquantifiable costs, such as risk of loss of life, loss of public trust, and political fallout. Ignoring consequences of rupture results in improper expenditure of resources without achieving the reliability desired, but assigning unrealistically high costs to the consequences of rupture results in unnecessary repairs and misallocation of limited resources. Multiple failures in a pipeline, without a publicly acceptable explanation, can result in significant reduction of public trust, increased public scrutiny, and political fallouts. In some cases, multiple ruptures have resulted in court-mandated actions that bind the utilities to a course of action that may not be the most prudent.

Unverified Technologies

Use of condition assessment technologies with unverified accuracy in detecting distressed pipes and in quantifying the level of distress in such pipes 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 in condition assessment, as bad pipes go undetected. Failure in accurately estimating the extent of distress will cause errors in determining how close the pipe is to rupture and results in either wasting of scare resources on unnecessary repairs or loss of reliability of the pipeline as highly distressed pipes remain unrepaired.

Overkill in Rehabilitation

Rehabilitation of a pipeline by either repairing all distressed pipes or replacing a section of pipeline containing distressed pipes, without adequate field verification of NDT results and without understanding the cause of the distress, is an ineffective use of limited resources. Utilities should recognize that corrosion and wire break are manifestations of the degradation process of a PCCP that typically takes many years to mature and reach a critical stage that causes pipe rupture under the applied loads. In some cases, the cause of failure is something other than the pipe, such as stray current, improper cathodic protection, and local environment, making repair without solving the root-cause problem ineffective in the long term. In most cases, PCCP with limited number of wire breaks can safely perform under the design loads and pressures for many years.

One reason why pipelines with low to moderate risk of failure are replaced or wholly rehabilitated is the misconception that good pipes subjected to the same environment as distressed pipes will soon become distressed. Sixty years of experience with PCCP shows that distress grows gradually and that the average fraction of distressed pipes in a pipeline is about 3.7% of the total. The number of distressed pipes with high risk of failure is an order of magnitude less than the number of distressed pipes, meaning that low-to-moderate-risk pipelines can be effectively managed and do not require wholesale rehabilitation.

What's Next?

The upcoming advances in condition assessment of PCCP include technological advances to meet the needs of utilities, establishment of an acceptable level of risk, modification of PCCP design methods to account for future distress, and deployment of emerging technologies.

Technological Advances

Technological advances are necessary to meet the needs of utilities in the areas of selecting a pipeline for inspection, discerning hydrogen embrittlement wire breaks from corrosion wire breaks, understanding and minimizing uncertainties in NDT results, and estimating remaining service life.

- Pipeline Criticality: Advanced methods of establishing pipeline criticality are needed in order to prioritize pipeline inspection and select the level of inspection required. Current methods of determining pipeline criticality using index systems and emerging technologies such as neural networks and fuzzy logic that use of artificial intelligence need to be refined and verified.

- Hydrogen Embrittlement: Discerning wire breaks due to hydrogen embrittlement from wire breaks due to corrosion is important because embrittled wire tends to break at random locations along the length of the pipe and around the circumference, resulting in significant amounts of residual prestress in the distressed pipe.

- Uncertainties: Practical limitations and uncertainties in the application of NDT technologies should be identified and eliminated through research. There is a need for understanding by utilities and the consultants of the uncertainties of NDT inspection results so that the uncertainty can be considered in failure margin and risk analysis. Specifically, acoustic monitoring results need to be verified by external inspection, and electromagnetic inspection accuracy near the joint and for special pipe designs, such as pipe with thick steel cylinder, is not adequate.

- Remaining Service Life: The remaining service life of a pipe can be established from knowledge of failure margin in terms of the number of wire breaks to rupture and the rate of wire breaks expected to occur. Data on the rate of failure can be site specific and obtained either by multiple electromagnetic inspections (see Zarghamee et al. [2]) or by acoustic monitoring. When a long history of site-specific inspection data is not available, non-site-specific data can be used to estimate the rate of wire breaks.

Establish Acceptable Level of Risk

Utilities have different risk aversions and do not believe that there is a single acceptable risk that can be defined for all utilities; rather, the acceptable risk depends on many factors that differ from utility to utility and should be defined for each utility. More work is needed in this area to help the utilities define their risk aversion.

Modify PCCP Design Methods to Account for Future Distress

The tolerance of PCCP to distress, expressed in terms of a number of broken wires, is quite different for different pipe designs subjected to different external loads and pressures. There is a need for building a certain level of distress into the design process of PCCP so as to reduce the sensitivity of the pipe-rupture pressure to distress.

Emerging Technologies

Some new technologies for condition assessment of PCCP are currently in the development stage. These include technologies for detection of wire breaks based on pipe-wall stiffness and on inductive scan imaging (an electromagnetic method for detection broken wires from the exterior of an excavated pipe). Stress-wave-propagations methods (e.g., impact echo and spectral analysis of surface waves) have been used for detection of prestress loss, but the results are not conclusive. Development is underway for electromagnetic inspection technology to detect corrosion of the steel cylinder in LCP. Laser profiling inside of pipelines has been used to quantitatively evaluate the pipeline interior surface for irregularities such as spalling, deterioration of inner core, and inside joint mortar loss for small-diameter pipelines that cannot be visually inspected.

Conclusions

The following conclusions are made based on the results of comprehensive literature review and analysis of the results of industry survey and workshop:

- Condition assessment of PCCP identifies distressed pipes, estimates the level of distress, analyzes their margin to failure, determines their failure risk, and repairs those pipes with unacceptable failure risk, thus keeping the pipeline reliability at an acceptable level. An approach to condition assessment is proposed that considers risk of failure (likelihood and consequence of failure), pipeline constraints, strengths and limitations of both conventional and advanced condition assessment technologies, and economic value of rehabilitation methods.

- The Best Practices Guidance Manual developed by this project assists water utilities in selecting appropriate technologies for condition assessment, performance monitoring, and failure margin analysis of their pipelines to maintain acceptable pipeline reliability.

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