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Determining a Reliability Centered Maintenance (RCM) analysis model for large diameter prestressed concrete water pipelines

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Abstract

Which maintenance task to perform on an asset is generally known but the schedule of when to perform the task may not be well defined. If the task is performed early, while it may benefit the asset, it may also be expending resources that could be better used elsewhere. If the task is not performed soon enough, the asset may fail, or the asset may require more extensive maintenance be performed. Reliability Centered Maintenance (RCM) is an analysis process used to determine the most effective maintenance strategies. RCM analysis can help an agency establish the most cost effective maintenance strategies for an asset and help establish the best schedule for implementing those strategies. The ultimate goal of an RCM is to determine the required function of an asset with the required reliability at the lowest operation and maintenance costs by identifying revealing indicators of potential failures to establish a condition based strategy; essentially, predicting failures and identifying procedures to minimize the risk of the failure. This paper reviews potential models for predicting the progression of distress of prestressed concrete pipe segments for use in an RCM analysis and proposes a regression model operators can use to forecast when to perform maintenance activities. The paper further considers the condition of the drinking water infrastructure in the United States, developing the case for evaluating predictive models to forecast when a pipeline may reach a specified limit state. The results of this study suggest that RCM analyses for large diameter water pipelines can improve reliability, reduce maintenance costs, and extend the useful life of a pipeline regardless of age or material. Further, using a regression style model with gathered data can be used to forecast when specific maintenance thresholds may be reached, prompting predictive maintenance actions.

Keywords: Reliability-centered maintenance; RCM; Water pipelines; wire breaks; Prestressed concrete pipe; PCCP; Acoustic fiber optics; AFO; Numeric model; Pipeline inspection

1. Introduction

Determining when to perform maintenance tasks on an asset is often an uncertainty. Waiting too long puts the asset at risk of failure; performing too early can be a waste of resources that could have been used on other assets. For prestressed concrete water pipelines one known failure mechanism is breaking of the prestressing wires, sometimes due to mishandling during installation, sometimes due to hydrogen embrittlement of the wires, but more often due to corrosion. A few broken wires do not necessarily mean the pipe is at risk of immediate failure, but several broken wires in close proximity may require maintenance be performed on the pipe to restore its condition. The maintenance tasks undertaken are the decision of the operating agency and can range from slip lining to carbon fiber application, installing external post-tension tendons, or even replacement; however, when to perform the task is often not understood.

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Inspecting pipelines can help utility operators determine the condition of a pipeline, but often that condition is merely a snapshot in time. Performing multiple inspections to gather the same data over time can help look for trends, but those trends then need to be forecast to establish a potential condition in the future. It can take several inspections over many years to gather enough data to develop an accurate model. Fortunately for prestressed concrete pipes there are well proven methods for detecting wire breaks such as electromagnetic (EM) inspections (a snapshot in time) and acoustic fiber optic (AFO) monitoring systems (condition based monitoring).

Prestressed concrete pipe is typically a large diameter water pipe capable of withstanding high internal pressures while often buried deeper than pipes of other materials. The performance of prestressed concrete pipe is governed by the compressive resistance of the concrete to the overburden and the tensile properties of the steel prestressing wires to the internal hydraulic pressures. If enough of the prestressing wires break, the pipe is subject to failure, leakage if a relatively low pressure system, or explosive release if operating at a higher pressure. Predicting when enough wires are broken to result in a failure will help agencies establish a schedule for performing maintenance tasks. This paper looks at several models for forecast when prestressed concrete pipe may reach a specified limit state and considers a regression model for further use for forecasting wire breaks in prestressed concrete pipes.

2. Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance (RCM) is a decision methodology to develop applicable and cost-effective proactive preventive and condition-based maintenance tasks to preserve the required functions of an asset or a system. Performing an RCM workshop can be thought of as performing a technical accounting of an asset or system that details the functions and functional failures of the asset or system and methodically leads the workshop team through a series of decisions to identify maintenance tasks to prevent or mitigate the occurrence of a functional failure. When a maintenance task is implemented based on the findings and recommendation of the RCM, it is easy to understand why that maintenance task was identified and the intended benefit. The RCM analysis provides for the complete understanding of an asset or system.

RCM is a technical accounting system that details the functions and functional failures of an asset and methodically leads an analyst through a series of decisions to prescribe maintenance tasks to prevent or mitigate the occurrence of functional failures. The goal is to establish the required function of an asset with the required reliability and availability at the lowest cost. RCM requires maintenance decisions be made based on maintenance requirements supported by sound technical and economic justification.

Failures can be predicted by identifying failure modes and causes associated with system functional failures and describing the effects (consequences) of failure. This helps identify predictive signs of potential failures providing for a more aligned condition-based strategy. Allen et al. [1] stated that, “If we fully expect that all expenditures of a company be thoroughly documented by sound accounting standards for future audit, then why would we expect less for documenting the purpose of a company’s assets and the strategy in preserving their need?”. During an RCM analysis, teams are prompted to consider tasks that identify and address failure modes that require assessment of the system’s condition [2].

A failure mode describes “what went wrong” (i.e., pipe leaks), while a failure cause describes “why it went wrong” (i.e., the internal lining on a steel pipeline deteriorated due to erosion and allowed the substrate to corrode). It is more than just another way to perform maintenance, it is a way of looking at system performance in terms of the impact of a failure and then mitigating those results by design, detection, and/or effective maintenance. It is nearly impossible to prevent all failures; however, it is possible to develop a maintenance strategy that could prevent some failures. The essence of RCM is to manage the consequences of the failure, not necessarily prevent failure. One of the most beneficial products of an RCM analysis is the identification of the best proactive maintenance tasks such as on-condition maintenance, scheduled restoration, replacement, and even scheduled discard tasks. With these maintenance tasks, possible failure modes and their consequences are identified while the function of the asset is considered. The most effective techniques are then selected to improve the reliability of the asset [3]. RCM is one of the most effective maintenance approaches capable of reducing maintenance activities and their related costs without affecting the overall performance of the equipment, quality, safety, and environmental integrity [4]. The result of an RCM program is the implementation of a specific maintenance strategy on each of the assets of the system. Figure 1 illustrates the four available outcomes of an RCM analysis.

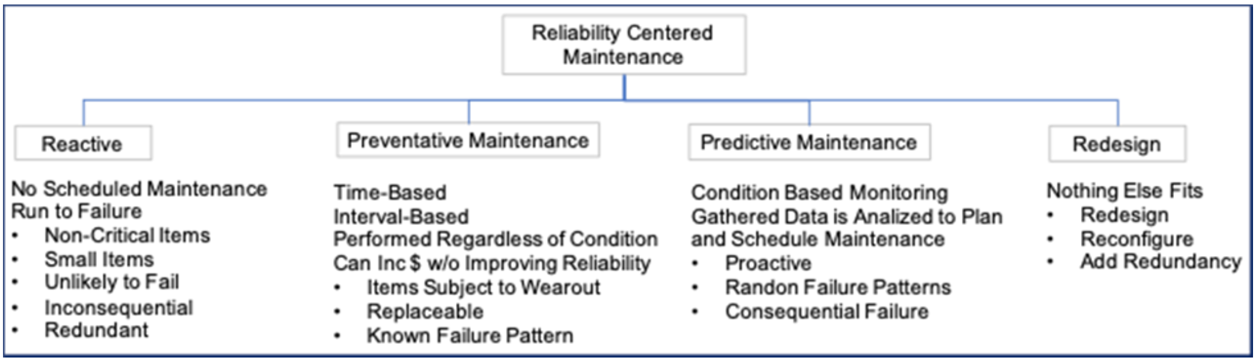


Figure 1 RCM Outcomes

Reactive can be thought of as “run-to-failure”, or “no-planned-maintenance”, essentially “fix it when it fails”. The asset or system is operated until it fails, at which point it is repaired or replaced. These are most likely non-critical items unlikely to fail, and if they do fail the effect is of minor consequences, or the components or system have redundancy built in. Consider a simple light bulb – it is not serviced; it runs until it fails and is then replaced.

Preventative Maintenance can be thought of as “time-based” or “interval-based”, performing a task based on time or operating cycles. It is a proactive maintenance strategy that involves regular and routine maintenance of an asset to reduce the likelihood of failure. Examples include regular cleaning, lubrication, and/or replacing of parts. Consider changing the oil in a vehicle every 4,800 km (3,000 miles). A vehicle may be able to travel further than 4,800 km (3,000 miles) and by changing the oil resources may be wasted. Opposite to that, 4,800 km (3,000 miles) may be too infrequent depending on the operating environment and damage may be incurred by changing too infrequently. The exact time to change the oil is unknown, but optimistically the selected time is preventing damage without expending too many unnecessary resources. The asset is often easily replaceable and has a known failure pattern.

Predictive maintenance is based on gathering and analyzing data (condition base monitoring) to establish scheduled maintenance tasks. These assets often have a random failure pattern and a relatively high consequence of failure. Measuring the temperature on a motor or the vibration on a pump and establishing a specific task when a certain threshold is met, are examples of predictive maintenance.

Redesign can be merely adding redundancy to a system or asset, reconfiguring the layout to provide redundancy, altering the way it is operated, or completely creating a new design to meet one of the other three potential outcomes are examples of redesign.

RCM helps the operator of an asset perform the correct maintenance task at the correct time. Implementing a Reliability Centered Maintenance workshop is a detailed process of evaluating an asset to:

- Establish its function(s)
- Identify what functional failures may occur that may preclude the asset from fulfilling its function(s)
- Identify the failure modes that could cause the failure
- Review the likelihood and subsequent consequences of a functional failure (risk analysis)
- Identify tasks that could be developed to reduce the likelihood of a functional failure
- Establish costs for implementing maintenance tasks

Part of the RCM process involves a failure modes and effects analysis (FMEA) in which all the identified failure modes of an asset are analyzed, and the consequences of a failure evaluated. The FMEA is a structured approach to identify, document, and rank the importance of potential failure modes for a system or an individual asset, and analyze the potential impact a failure may have on the system. The FMEA is a major portion of an RCM used to develop maintenance strategies for whatever asset or even system is being analyzed.

Steps involved in the FMEA identify:

- Functions – what does the asset do
- Functional Failures – how the asset may fail to perform the intended functions
- Failure Modes – why the asset fails to perform the intended functions

- Failure Effects – what happens when the asset fails to perform the intended functions
- Severity of Failure – how bad is the failure
- Failure Frequency – how often does the asset fail
- Failure Detection – how are the failures identified

A failure mode, the way in which an asset could fail, can be thought of as "what is wrong" with the asset, and is defined as an unsatisfactory piece, part, or material condition that prevents the equipment from functioning as required – a failure mode is an unsatisfactory condition. Some failure mode descriptors are "corroded", "cracked", "buckled", "deteriorated", "frayed". Whereas the failure cause, or failure mechanism, can be thought of as "why did it happen", and some failure causes are "wear", "fatigue", "vibration", "corrosion", "age". The effects analysis is the process of studying the consequences of the failure.

The FMEA lays out a potential road map for a failure. By Identifying failure modes and their causes, associating them with functional failures and describing the effects of failure at three levels – the local, the system and the plant, the analyst is positioned to identify revealing indicators of potential failures to establish a condition based strategy; essentially "predicting failures" and identifying procedures to minimize the risk of the failure. An FMEA should answer how likely an asset or even a system is to fail, why the failure would occur, and if a failure occurs, how would it affect the surrounding environment and the safety of the operators. The goal of an FMEA is to increase reliability, performance, and safety. An FMEA also helps to prioritize deficiencies in a design or process and provides an opportunity to correct problems before they occur. Large diameter water pipelines are one asset in the drinking water infrastructure that would benefit from an FMEA during an RCM analysis.

3. Drinking Water Infrastructure

Drinking water infrastructure is vital to public health and for sustaining life. The U.S. uses 260 billion liters (42 billion gallons) of water every day for cooking, cleaning, and bathing in homes, to use in manufacturing facilities, medical facilities, and offices across the country, with approximately 80% of that water coming from surface waters such as rivers, lakes, reservoirs, and oceans, with the remaining coming from groundwater aquifers [5]. Not everyone lives near a source nor are all the water demands adjacent to a source. Subsequently, water must be transported to the user, most often via pipelines. The 2021 American Society of Civil Engineers (ASCE) Drinking Water Report indicates the United States drinking water infrastructure system is composed of 3.55 million km (2.2 million miles) of underground pipes that deliver safe reliable water to millions of people. Some of the nation's oldest pipes were installed in the 19th century, and pipes that were placed post-World War II have an average life span of 75 to 100 years, meaning that many of them are reaching the end of their design life [6]. Subsequently, much of the underground pipeline network is due for replacement within the next 20 years. Most people do not recognize that the lifespan of a system and components comprising the system require regular maintenance to meet that expected lifespan.

It is estimated that 6 billion gallons of potable water leaks from pipelines each day in the United States. Alarmingly, roughly 14% to 18% of the water treated to meet potable standards never reaches the end-user. This translates to a daily loss of potable water that could support 15 million households [5]. Lost water means lost revenue for an agency because water that never arrives at its destination cannot be metered and the water system does not collect payment for treating/delivering the water. This could actually be a twofold loss in some cases. Consider that a utility uses resources (spends money) it cannot regain from treating water and the water is lost – leaks into the ground. Water from a heavily used source is removed from the source and essentially lost. If it were never removed, it could be saved and used another time. The direct cost of leaks is estimated to be $2.6 billion per year [7].

ASCE estimates that the United States needs to invest an additional $82 billion USD in water infrastructure per year over the next decade at all levels of government. Between 2013 and 2020, it is estimated the cumulative cost to households from degrading systems was $59 billion, with the cost to businesses $147 billion USD. The American Water Works Association (AWWA) estimates $1 trillion USD is required to maintain and expand service to meet demands over the next 25 years [8]. A recent analysis indicates that a reduction in the nation's gap in investment in water infrastructure would create 1.3 million jobs and generate $220 billion USD in economic activity [9]. The same analysis also found a severe economic cost to inaction. At a national level, a one-day disruption in water service can lead to a loss of $43.5 billion USD in sales and $22.5 billion USD in gross domestic product (GDP). At the local level, industries most reliant on water would see sales drop by up to 75 percent due to a one-day disruption in service. People depend on clean reliable water for everyday activities, and without that supply lives would be quite different. The American Water Works Association (AWWA) reported that the top issue facing the water industry since 2016 is aging infrastructure with the second being financing for improvements [8]. The water industry needs to find ways of extending asset life, while also reducing maintenance expenditures. While there are many different assets comprising the water/wastewater industry, pipelines are a major component. Because pipelines are typically buried, they are often considered "out-of-site out-of-mind", resulting in them often being neglected.

Implementation of RCM to a utility's infrastructure can help reduce maintenance costs and extend an asset's usable life. RCM's approach is to analyze an asset and system with the intent of developing maintenance strategies to maximize function and minimize failure. A meticulously planned and executed RCM strategy should reduce the risk of a major failure. Considering the state of pipeline infrastructure in the U.S., it is recommended water utilities look at ways to adopt RCM to examine their maintenance practices and determine if there are more cost effective and efficient preventative maintenance activities that could be implemented. In particular, large diameter water pipes (> 42 inches) should undergo regular maintenance since they are such a critical asset in the drinking water infrastructure [10]. The consequences of failure are significant, not only the loss of water, but a failure can lead to significant costs and property damage. For example, in 2016 a 5.3 m (17.5-foot) diameter water pipe failed on the Navajo Indian Irrigation Project (NIIP) near Farmington, New Mexico. In addition to the estimated 3.8 million liters 1,000,000 gallons) of water lost, the repair cost exceeded $1.5 million USD; however, even more significant, was the estimated $17.5 million USD loss of crop revenue [11].

However, aging infrastructure does not have to equate to a reduction in reliability. The application of a strategic RCM program can significantly improve reliability, reduce maintenance costs, and extend the useful life of infrastructure assets regardless of age. An area for further study to use RCM for water pipeline infrastructure is the determination of suitable models to use when analyzing a pipeline and the applications for developing maintenance procedures. A modeling approach would provide a quantitative methodology for exploring the applicability and results of RCM for large diameter water pipelines. If pipes can be identified before they completely fail, water utilities will be able to maintain or replace them on a scheduled rather than an emergency basis, significantly reducing operating costs. With the aid of these strategies whole of life costs and operating lifetime can be optimized [12].

Many utilities across North America and the world use large diameter prestressed concrete cylinder pipe (PCCP) in their water transmission systems. While most of this type of pipe has no problems, the predominant failure mode is loss of prestressing wires, generally due to corrosion. Being able to accurately predict when a pipe may experience enough loss of prestressing wires to fail will enable agencies to plan for maintenance activities ahead of a failure. Pipelines represent more than 80% of the total asset value of water systems, therefore accurate and timely maintenance practices are critical to balancing ever decreasing maintenance budgets.

4. Models Used for Pipeline Maintenance Identification

A recommended area for further study to use RCM for water pipeline infrastructure is the determination of suitable models for analyzing a pipeline and the applications for developing maintenance procedures. A modeling approach would provide a quantitative approach for exploring the applicability and results of RCM for large diameter water pipelines [13]. Several models such as finite element have been developed to consider the strength of a pipe; in the case of PCCP, the number of wires breaks that may cause the pipe to fail under a particular operating pressure. However, a bigger issue facing pipeline owners is knowing when the number of wire breaks may reach the point where a pipe may fail. If the approximate time a pipe may fail or reach a specified limit state can be determined, agencies can begin planning and scheduling for specific maintenance tasks that can extend the life of the pipe. Knowing the expected time of failure can provide an agency the opportunity to plan and budget for maintenance activities and even plan for removal from service for a specified time if necessary to conduct maintenance to restore the pipeline to a near-new condition. By planning the activities rather than reacting to a failure, an agency can potentially avoid expensive damage such as the social issues of a waterline failure, the water loss costs, and the expense of potentially replacing the damaged pipe rather than repairing it. In some cases, a failure of a single pipe section may cause damage to adjoining sections that then require repair or even replacement, further escalating the cost of the failure. It will also help agencies from conducting premature renewal or even replacement of pipes that still have many years of service remaining, allowing them to direct resources better used elsewhere.

Most models tend to evaluate how a pipe will fail, the failure mode, but not necessarily when. By being able to forecast when a pipe may fail pipeline operators can back into a schedule as to when they should begin to plan for budgeting for maintenance activities to prevent the failure by scheduling maintenance activities, coordinating service shutdowns if required, notifying downstream users (customers) of anticipated outages so they can plan for an outage. Performing maintenance tasks on a pipe should increase the life of the pipe, but if a task is performed before it is required, the pipeline owner could have better used those resources on another system asset.

Failure modes of PCCP are well documented; however, the time to perform specific maintenance tasks to rehabilitate a pipe back to near new conditions is not. To help "predict" failure, various models have been used, including Weibull Hazard models and Artificial Neural Networks. Past failure events are required for those models. If a pipeline has several known deteriorated pipe segments, but has not yet experienced a failure, the question that needs to be answered is "when should those distressed pipe segments have maintenance performed?". Using conditioned based monitoring and analyzing data from inspections, a model can be developed to forecast when a pipe may reach a certain threshold, or limit state, and alert pipeline operators when to begin planning for maintenance tasks.

Many water authorities and agencies around the world use PCCP in their transmission and distribution systems. The evaluation of the performance of these systems becomes a major concern for owners and operators. The Great Man-Made River Project, a large PCCP transmission system in Libya, experienced several ruptures in one of their pipelines due to corrosion induced failure of the prestressing wires. Amaitik and Amaitik [14] discussed an Artificial Neural Network (ANN) model to predict the condition and performance assessment of pipelines based on historical condition observations and inspection results. The objective was to develop a PCCP wire break prediction model to provide owners and operators of PCCP water pipelines a method of determining if and when deterioration of their pipelines may be occurring so they will be able to make informed decisions about monitoring, inspection, and rehabilitation of their pipeline network. The output of the model is the number of wire breaks which is considered the most important factor in evaluating the condition and performance of PCCP. The model can fairly accurately predict which pipe segments will experience wire breaks, but not the timing of the breaks to determine when to perform maintenance tasks. However, the output can be used to determine which pipelines should be monitored more closely.

Being able to predict the remaining useful life and deterioration rates of pipelines will help agencies use more cost-effective maintenance measures which can include replacement of pipe pieces and even entire pipelines, but also prevent premature renewal or replacement of pipes in good condition. Zangenehmadar and Moselhi [15] used artificial neural network models in water distribution networks to forecast the remaining useful life of pipelines based on physical characteristics to develop data driven optimized maintenance plans. They suggest performance models mostly predict the future behavior of pipelines while ANN models are mostly applied in predicting pipe failure and condition rating, but ANN models are limited in that they are site specific and unable to predict upcoming failure rates for other areas, [15]. However, ANN models are able to cover numerous variables and non-linear and complex behavior of water networks which increase system performance reliability and holds merit in comparison to other methods. They further emphasized that identifying the remaining useful life will help in performing more economical and cost-efficient replacement and maintenance measures such as allowing resources to be better expended elsewhere.

Hajali et al. [16] used nonlinear finite element analysis (FEA) to evaluate the location of broken wire wraps in PCCP to determine if wire breaks at one location along the pipe segment was worse than another. The results show that broken wire wraps at the joint, and especially the spigot joint, decrease the overall strength of PCCP more so than those at the bell joint or in the barrel of the pipe. A downside is that this study does not help an agency decide when to perform specific maintenance tasks. However, if an agency has known distresses at critical locations along a pipe segment (i.e., the spigot end versus the pipe barrel), it can then focus on rehabilitation strategies on the pipe segments with distresses at the joints and perhaps delay maintenance on pipe segments with distress only along the barrel. Hajali and Shdid, [17], developed a three-dimensional computational model using nonlinear finite elements to simulate the behavior of buried PCCP under combined internal and external loading. The model was not aimed at predicting deterioration levels of PCCP, rather about creating a reliable FEA model for a PCCP that can be used in the future for different PCCP's with different levels of damage to determine the maximum pressure the pipe could sustain before bursting. Knowing an accurate maximum yield pressure for a pipe, pipeline owners can better decide about repair or replacement of the pipeline. The approach can predict with relative accuracy the deterioration levels of different pipe segments under realistic loading conditions considering the effect of the number and location of broken wires [17]. The maximum expected pressure in the pipe and the number of broken wires can be used to determine the repair priority for each distressed pipe and agencies can then identify those pipes that are at a high risk of failure and need of immediate repair, as shown in Figure 2. It is worth noting that the model does not help an agency decide when to perform specific maintenance tasks. There is no time element in the model estimating when a pipeline may require maintenance.

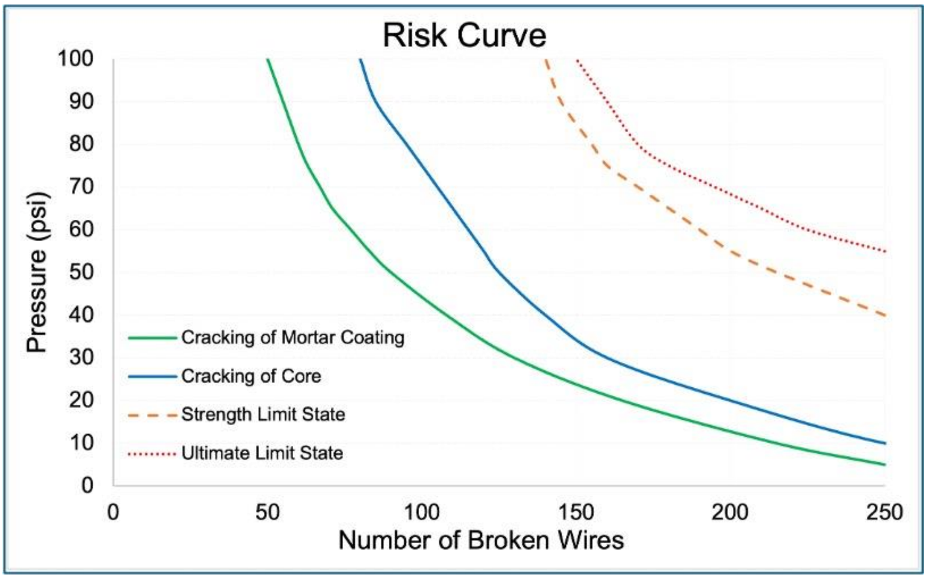


Figure 2 Risk Curve

Rajani et al. [18] described the use of fuzzy synthetic evaluation to translate inspection observations into condition ratings which reflect an aggregate state of a pipeline's health. However, the results are only based on the data gathered at a specific time. Performing the evaluation after multiple inspections can yield a trend in the overall condition of a pipeline but cannot predict a condition state at a future time. Pipeline operators can use this evaluation process to better understand a pipeline's condition, but not when to perform future maintenance tasks. Figure 3 illustrates changing pipeline conditions as a pipeline deteriorates, but it is not predicting when a condition will occur, and not on which pipe segment, merely the entire pipeline.

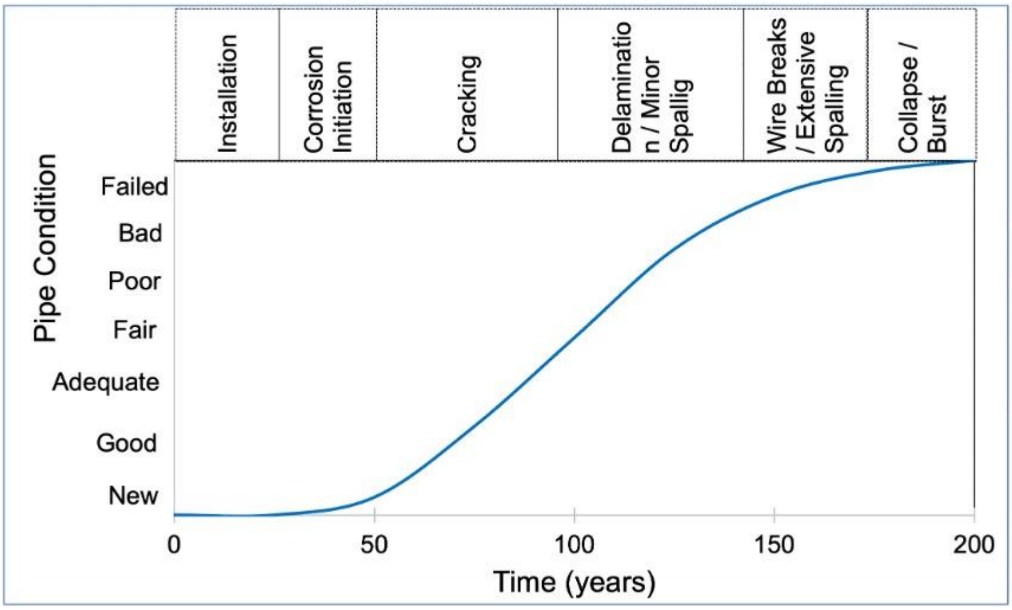


Figure 3 Change of Condition over Time

Tanaka et al. [19] describe using a Weibull Hazard Function to forecast the deterioration of pipelines and determine the optimal renewal time that offers the minimum expected life-cycle cost of a pipeline. The data used in the model is based on data gathered from failed pipes, not from data gathered from inspections or other condition assessment activities. If there is no break history in an agencies' pipe inventory, this type of model will not be of use.

Friedl et al. [12] proposed a bivariate logistic regression model to estimate specific failure mode probabilities, like circumferential cracking, longitudinal breaks, rupture, corrosion pitting, and leaking joint to determine a deterioration status and subsequently the main influencing cost parameters on the result of the optimum replacement time which are repair costs, rehabilitation costs, and costs for water losses. The water losses for different failure modes can be modeled with the orifice equation which describes the correlation between flow and pressure with a leakage-coefficient and leakage exponent. Failure modes describe how pipes fail while failure mechanisms explain why they fail. If pipes can be identified before they completely fail, water utilities will be able to repair or replace distressed pipes on a scheduled rather than an emergency basis, significantly reducing operating and maintenance costs. With the aid of these strategies life cycle costs of operations and maintenance activities can be optimized. However, there was no forecasting nor prediction of when a pipe may reach the point where intervention is necessary, prior to failure.

Zarghamee et al. [20] investigated the current number of distressed pipes and the level of distress of those pipes in two PCCP pipeline systems. Data was gathered from inspections occurring on average every 3 years over a 20 year period, but the first time the pipelines were inspected was about 20 years after the pipeline was installed. The level of distress was tracked through the inspection history to determine the rate of progression of distress and to determine if the progression rate depends on the current level of distress. Statistical models can be used to forecast the future level of distress and rate of progression of distress. A Weibull failure analysis was used for predicting new distressed pipes as well as for predicting an increase in distress level of already distressed pipes. The broken wire zone (BWZ) growth rate between inspections was also calculated and used in previously developed risk curves to determine repair priority. Risk curves represent the pressure a particular design of PCCP can resist with a given effective number of broken wires at specified thresholds such as serviceability limit, damage limit, and strength limit states. Predictive statistical models for distress in PCCP assets were presented, with the models forecasting the progression of distress as total number of distressed pipes (as a percent of entire pipeline) and total number of severely distressed pipes requiring repair or replacement, over the next 40 years. The rate of new distress pipe and the rate at which pipes enter Repair Priorities 1 and 2 (severely distressed) decreased over the pipelines life, while the number of distressed pipes increased. However, the model did not indicate which pipe segments would become distressed, and of the distressed segments, which ones would show an increase in distress level, it merely predicted an overall percent.

5. Proposed model

There are many finite element modeling/analyses in the literature modeling results from broken wires, but little about predicting when specific limit states or time along a P-F curve will be reached. Geisbush and Ariaratnam [13] illustrated the use of a linear regression model to forecast when a prestressed concrete pipe may experience enough wire breaks to reach specified limit states that will trigger maintenance tasks identified in an RCM to begin preparations for maintenance activities of those pipe segments. A significant amount of data is required to make a reasonably accurate estimation as to when a pipe may reach a specified threshold. Figure 4 is a graph showing wire breaks over time for a large diameter prestressed concrete pipe segment.

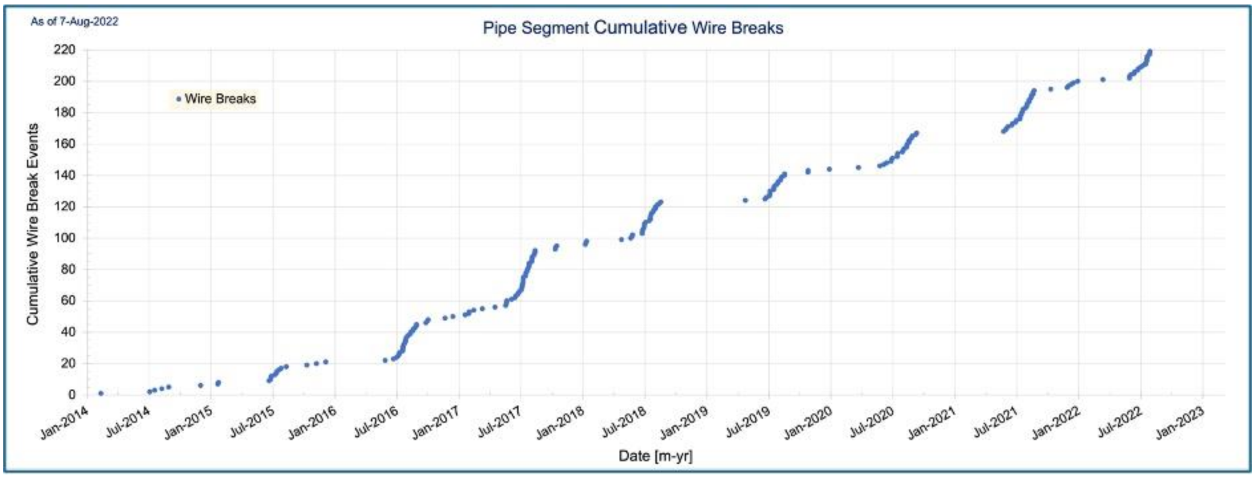


Figure 4 Cumulative Wire Breaks

The wire breaks were gathered in real time with an AFO monitoring system. The intent is to forecast when a specific number of wires are broken, reaching a specified limit state, similar to those shown in Figure 2, so that an agency can plan when to perform maintenance activities. Regression analysis can be used to derive an equation to predict or forecast when a certain number of wires may be broken. Figure 5 illustrates wire breaks trending over time in the pipe segment with a regression analysis used to estimate when the number of broken wires may reach a specific threshold.

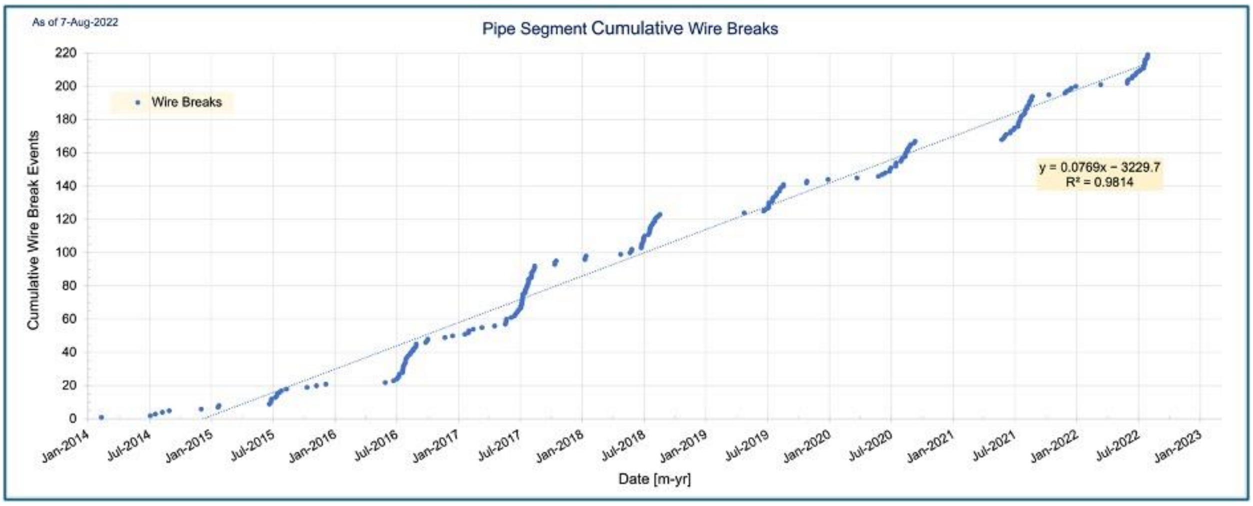
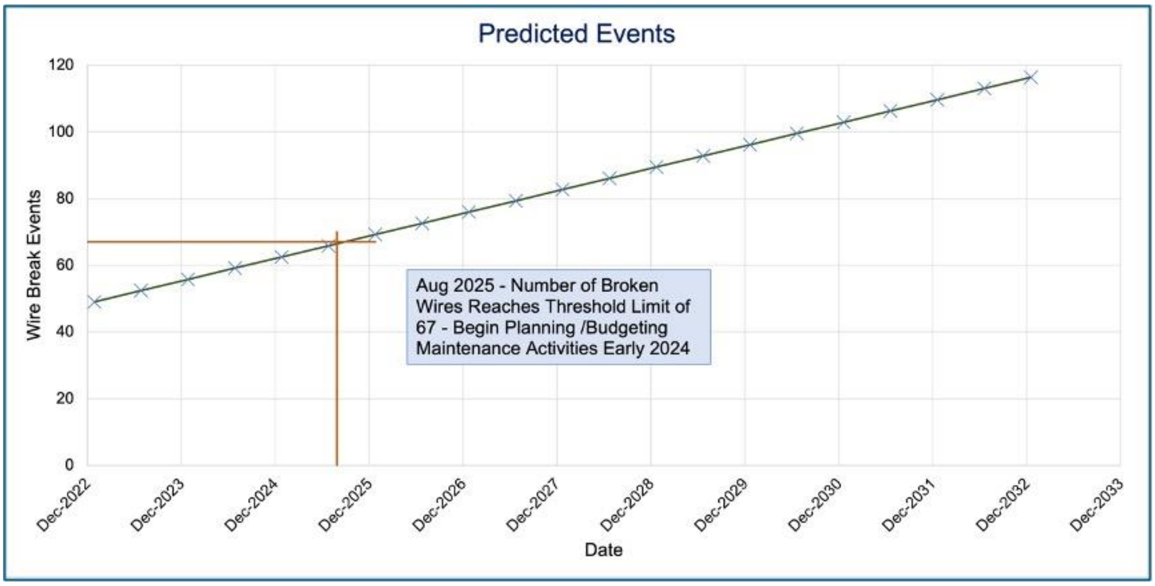


Figure 5 Pipe Segment with Cumulative Broken Wires and Regression Equation

The equation shown in Figure 5 can be used to predict or forecast when a specific threshold may be reached, shown in Figure 2 based on the operating pressure of the pipeline, so an agency may know when to begin planning for maintenance. Figure 6 illustrates the forecast date of reaching a specified threshold level. When that date is forecast an agency can determine when to begin planning and budgeting for maintenance activities and perform maintenance in a predictive mode, rather than reactive.



Aug 2025 - Number of Broken Wires Reaches Threshold Limit of 67 - Begin Planning /Budgeting Maintenance Activities Early 2024

Figure 6 Estimated Wire Breaks

Figure 7 illustrates a pipe segment in the same pipeline as the segment shown in Figure 5 but with different number and location of wire breaks along the pipe segment. The trend of wire breaks is similar, but quite different, considering the pipe segments are the same class and near each other in the pipeline. The regression analysis results in a similar but different equation.

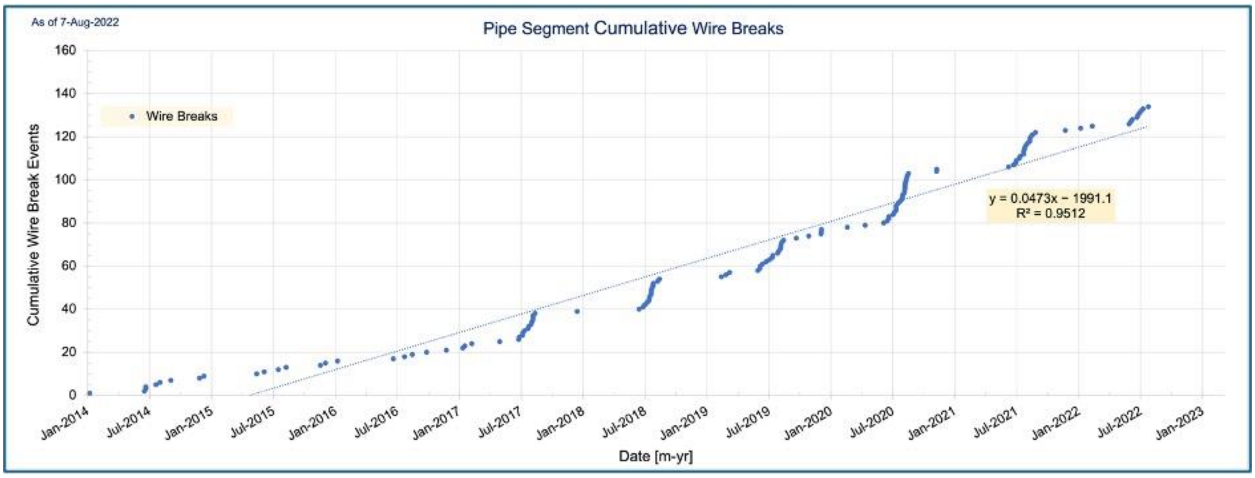
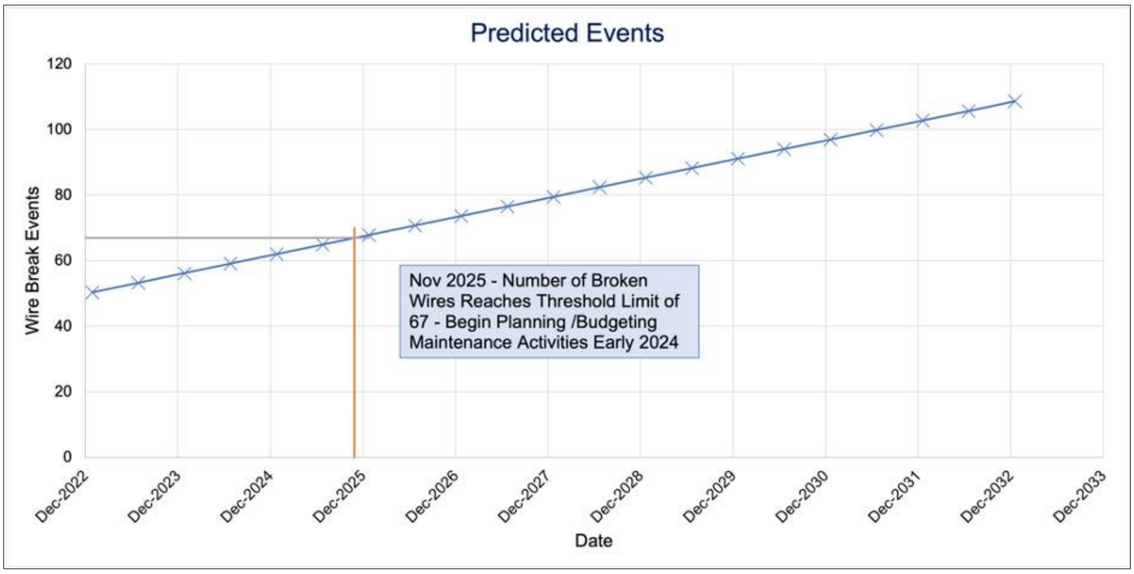


Figure 7 Nearby Pipe Segment with Cumulative Broken Wires and Regression Equation

The equation shown in Figure 7 can be used to predict or forecast when a specific threshold may be reached, shown in Figure 2 based on the operating pressure of the pipeline, similar to what was illustrated with Figure 5 and Figure 6. Figure 8 illustrates the forecast date of reaching a specified threshold level based on the analysis from the data in Figure 7.



Nov 2025 - Number of Broken Wires Reaches Threshold Limit of 67 - Begin Planning /Budgeting Maintenance Activities Early 2024

Figure 8 Estimated Wire Breaks for Second Pipe Segment

The result from the analyses shown in Figure 6 and Figure 8 indicate the predicted number of wire breaks will reach a specified threshold on both pipe segments in 2025. Knowing that predicted date, the operating agency could plan, budget, and schedule maintenance activities on both segments for the same time, and potentially save additional resources by reducing mobilization activities.

6. Conclusions

Large diameter water pipelines are the primary conveyance system of many agencies, and their failure can have severe consequences. Predicting their failure is crucial to planning their inspection, maintenance, and repair and/or rehabilitation, prior to a failure. Even pipelines that have reached the end of their design life can have extended service for many more years so long as proactive condition assessment and preventative maintenance tasks are part of the maintenance strategy. The implementation of a strategic RCM program with an understanding of pipeline failure modes allows an agency to significantly improve reliability, reduce maintenance costs, and extend the useful life of a large diameter water pipeline regardless of age. Knowing when to implement maintenance tasks is critical to maintaining a reliable system without expending unnecessary resources. Of all the models reviewed in this paper, regression analysis is the most straight forward in forecasting when there will be a quantified number of broken wires sufficient to reach a specified limit state, or approaching the limit state, for an agency to begin planning more detailed maintenance tasks and perhaps intrusive interventions, such as removing the pipeline from service while maintenance is performed.

The data used in this article are from one water agency in the southwestern United States and specific to the pipelines being monitored. The results concluded herein are only applicable to the specific pipe segments for which the data was analyzed, but the methodology is applicable to other pipelines. The pipelines discussed herein have known distress of several pipe segments, some of which have been repaired during previous maintenance activities. The AFO system was installed to monitor their conditions, prompting this analysis to determine when to begin planning for the next maintenance activities. The methodology discussed herein can be used by other agencies and operators of prestressed concrete pipes, and for agencies with known distress this analysis should help them better schedule maintenance tasks.

Agencies can use a predictive schedule to know when to allocate resources to specific assets, or how to prioritize maintenance on assets. The intent of maintenance is to prevent failure, not restore an asset after failure. Large diameter water pipelines are “forever assets”, meaning that as long as they are maintained, they can last almost indefinitely.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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