STATISTICAL ANALYSIS OF CONDITION ASSESSMENT DATA AND PREDICTION OF FUTURE PERFORMANCE OF PCCP

Mehdi S. Zarghamee*, F. ASCE, P. Graham Cranston[†], Roger Fongemie[‡], and Daniel Wittas**

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[*] Simpson Gumpertz & Heger Inc., 41 Seyon Street, Waltham MA, 02453. E-mail: mszarghamee@sgh.com.

[†] Simpson Gumpertz & Heger Inc. Email: pgcranston@sgh.com

[‡] Arizona Public Service Company, 5801 S. Winterburg Road MS 7990 Tonapah AZ, 85354. Email: roger.fongemie@aps.com

[**] Arizona Public Service Company. Email: daniel.wittas@aps.com

ABSTRACT

This paper presents the benefits of a well-managed, long-term asset management program in determining the current condition and predicting future deterioration of prestressed concrete cylinder pipe (PCCP). More than 10 years of inspection and monitoring data were analyzed, accumulated from Palo Verde Nuclear Generating Station (PVNGS), operated by the Arizona Public Service Company (APS).

Pipe segments were inspected every 3 years on average. These data were analyzed to determine the current condition of the PCCP assets, and to develop statistical models of future deterioration of the pipeline and future deterioration rates of distressed pipes in different repair priorities by tracking individual deterioration zones throughout the inspection history. Using established risk and uncertainty analysis techniques, future repair priorities are forecast.

The frequency of inspections and quality of the data collected allowed us to develop meaningful predictive statistical models of deterioration in PCCP assets. Starting from the detailed data on distress levels in the pipelines, the models forecast future progression of distress, including the total number of distressed pipes, total number of highly distressed pipes requiring repair or replacement, areas of severe distress, areas of rapid deterioration, and specific pipe segments reaching severe distress level in a specific future time period. The inspection data and results of this study were incorporated into a Geographic Information System (GIS). Such information is of paramount importance for effective PCCP asset management.

Keywords: Prestressed Concrete Cylinder Pipe (PCCP); condition assessment; distressed pipe; statistical modeling; Weibull failure analysis; Geographic Information Systems (GIS)

INTRODUCTION

The Arizona Public Service Company (APS) operates the Palo Verde Nuclear Generating Station (PVNGS) located 45 miles outside Phoenix AZ. The plant has an installed capacity of 3.9 GW, the largest nuclear generating facility in the United States. Cooling water to PVNGS is provided from nearby municipalities though 194,000 ft of 114 in., 96 in., and 66 in. Prestressed Concrete Cylinder Pipe (PCCP) transmission main known as the Water Reclamation Supply System (WRSS). Three Circulating Water System networks (CWS) – each approximately 3500 ft in length – circulate cooling water between cooling towers and heat exchangers of the three generating units. Both systems were installed by 1980, and were later placed under cathodic protection in 1984 (CWS) and 1997 (WRSS).

Between 1999 and 2009, APS collected and compiled data from 46 RFTC inspections of PCCP assets at PVNGS, covering both the WRSS and the CWS; pipes were inspected every 3 years on average. This study investigates the current number of distressed pipes and the level of distress in those pipes. The level of distress is tracked through the inspection history to determine the rate of progression of distress, and to determine whether that rate depends on the current level of distress. Finally, statistical models are then applied to forecast the future level of distress and rate of progression of distress in the WRSS and CWS lines.

METHOD OF APPROACH

A distressed pipe is a pipe where RFTC inspection has detected broken prestressing wires. This study treats the WRSS and CWS lines separately, since the environment and operating characteristics of each line are very different. The current level of distress in each system is defined as the fraction of pipe segments in the line which are currently, or have ever been distressed. That is, distressed pipes which have since been repaired are considered distressed. It is essential not to remove repaired pipes from the population of distressed pipes; otherwise, the statistical models, which predict future distress, will underestimate the rate of new distressed pipe.

The severity of distress for a given pipe is determined by Risk Analysis [Zarghamee et al. 2003]. The procedure involves the development of risk curves which represent the pressure a particular design of PCCP can resist with a given effective number of broken wires at serviceability, damage, and strength limit states, similar to the limit stated used for the design of PCCP (refer to AWWA C304-07). The effective number of broken wires includes allowances for uncertainties and the expected BWZ growth in the next 5 years. A pipe with a maximum expected working-plus-transient pressure and a given effective number of broken wires at or beyond the strength limit state curve is said to be in Repair Priority 1. A pipe at or beyond the damage limit state curve – which corresponds to wide cracks in the concrete core and/or high stresses in the prestressing wire – but not at the strength limit state curve, is said to be in Repair Priority 2. A pipe that has broken wires but the extent of distress has not reached the serviceability limit state curve is said to be in Repair Priority 4. Pipes in Repair Priorities 1 and 2 are considered severely distressed.

The inspection data, as well as the distress severity and forecast distress levels were incorporated into a Geographic Information System (GIS). Using the database of the volume of data generated by inspections, we developed subroutines to perform statistical analysis and develop reports that assist . asset management decisions and planning.

Weibull analysis has been used previously to predict distress levels and failure rates in cast iron [Park et al. 2008] and PVC [Davis et al. 2007] pipelines. Romer et al. [2008] describe the use of a three-parameter Weibull distribution for failure analysis for PCCP. In this paper, models are developed for both entry of pipes into the set of distressed pipes, and for the entry of pipes into the set of pipes in Repair Priorities 1 and 2 (i.e., "severely distressed pipes") using a two-parameter Weibull distribution [Miller and Freund 2005, Weibull 1951].

QUANTIFYING DISTRESS

Inspection data were analyzed to track individual BWZs through time. Two goals are accomplished by linking each BWZ through the inspection history; first, it permits us to determine the actual growth rates of individual BWZs at different distress levels, and secondly, it permits the identification of new distressed pipes and new BWZs, and to determine the rates at which new distressed pipes new BWZs develop. The matching algorithm developed to track individual BWZs through time successfully matched 90% of BWZs in the WRSS, and 82% of BWZs in the CWS. A further 1.6% and 3.1% of BWZs in the WRSS and CWS, respectively, appeared as new zones in the most-recent inspection of a pipe segment and therefore could not be matched.

Distress levels were expressed in terms of Repair Priorities as described in the previous section. Based on maximum expected pressure in the pipe and an effective number of broken wires. This procedure produced a history of the repair priority for each BWZ through time, which is necessary for tracking – and later predicting – the progression of distress, and also for exploring whether BWZ growth depends on the severity of distress, both of which are developed in the following section.

Table 1. Distress in the WRSS and the CWS at PVNGS.

Description	WRSS	CWS
Number of Pipes which have inspection records	8232	648
No. (%) of pipes which show (or have shown) distress	696 (8.45%)	232 (35.8%)
No. (%) of severly distressed pipes (Repair Priorities 1 & 2)	108 (1.3%)	10 (1.5%)
No. (%) of Pipes with distress recorded in 1st Inspection	581 (7.1%)	178 (27.5%)
No. (%) of Pipes with no distress recorded in 1st Inspection	7651 (92.9%)	470 (72.5%)
No. of Pipes with new distress after 1st Inspection	114 (1.49%)	54 (11.5%)
Average No. of years between first and last inspection record of a pipe	8.09	8.53
Average Rate of New Distressed Pipe	16.1	9.21
(No. (%) of New Distressed Pipes in the Pipeline per year)	(0.185%)	(1.42%)

During the data reduction described above, several parameters describing the state of distress in the two systems were calculated. These are presented in Table 1. Inspection results and distress level data were incorporated into a GIS to assist asset management decision-making.

PREDICTING DISTRESS

In the previous section, we described how the inspection data were reduced to identify new distressed pipes, and to track the development of BWZs through time and the accompanying progression through the repair priorities. Now, statistical models will be applied to the forecasting of future distress, and to explore whether BWZ growth depends on the severity of distress.

New Distressed Pipes

We conducted a Weibull failure analysis by fitting a two-parameter Weibull distribution to the data for prediction of new distressed pipes. The probability density function for the Weibull distribution is shown in Eq. 1, where t is the time to failure, and α and β are the scale and shape parameters, respectively.

$$P(t;\alpha,\beta)=\frac{\beta}{\alpha^{\beta}}t^{\beta-1}e^{\left(-\frac{t}{\alpha}\right)^{\beta}} \tag{1}$$

An important consideration in fitting the Weibull distribution to the data is incubation period, the time from installation to the time when failures begin. The random variable t in Eq. 1 is in fact the time from the end of the incubation period, not the time from installation. For this analysis, incubation periods of 0 years – assuming failures began immediately following installation – and 10 years were considered. Note that the first inspections were approximately 20 years following installation, and significant distress was present in both systems at that time (see Table 1).

An important quantity which can be derived from the failure analysis is the failure rate or hazard function of the Weibull process, $h(t;\alpha,\beta)$, as expressed by Eq. 2. Depending on the value of the shape parameter β, the failure rate $h(t;\alpha,\beta)$ will be either decreasing ($\beta < 1$), constant ($\beta = 1$), or increasing ($\beta > 1$).

$$\mathrm{h}(\mathrm{t};\alpha,\beta)=\frac{\beta}{\alpha}\left(\frac{\mathrm{t}}{\alpha}\right)^{\beta-1} \tag{2}$$

The plots in Figures 1 and 2 show the total number of distressed pipes measured by RFTC inspection, the fit Weibull distributions for a 10-year incubation period, and the accompanying failure rate curves for the WRSS and CWS, forecast to 2050. Discussion of the results follows in the next section.

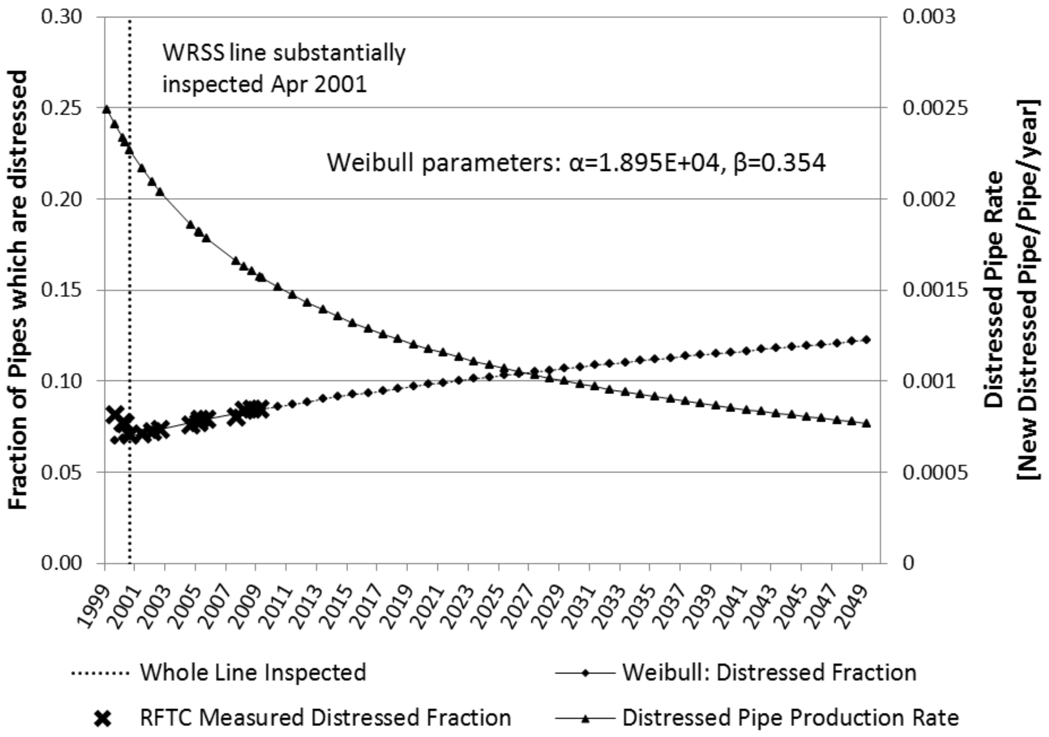

Figure 1. Prediction of new distressed pipes in WRSS based on a two-parameter Weibull distribution.

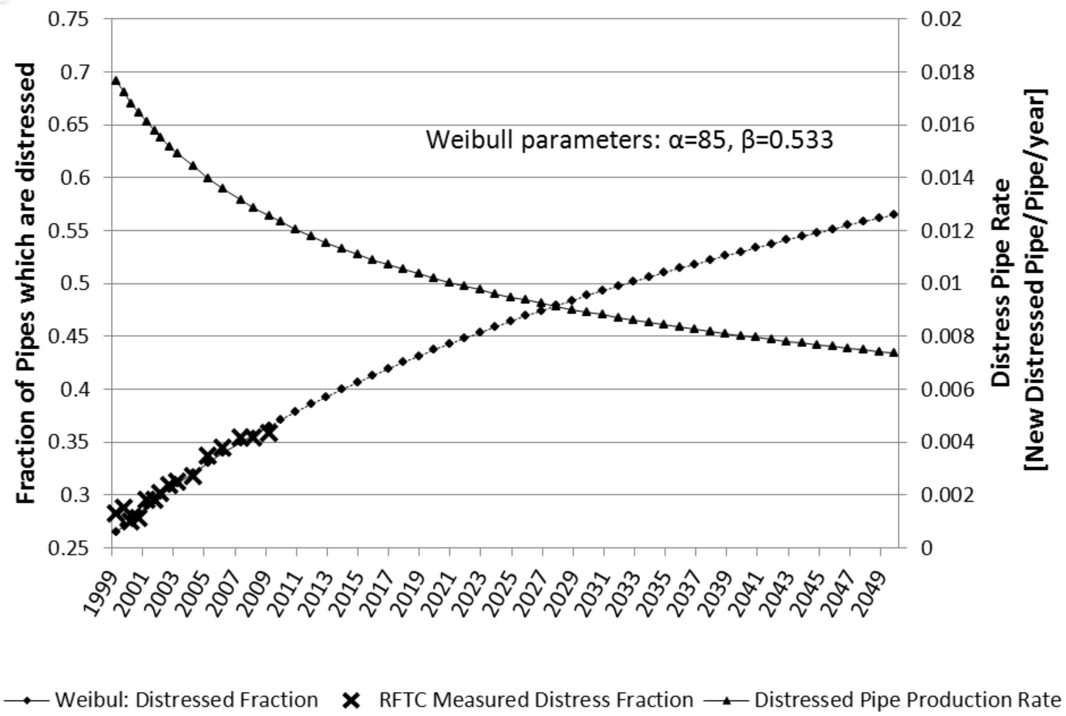

Figure 2. Prediction of new distressed pipes in CWS based on a two-parameter Weibull distribution.

New Severely Distressed Pipes

We conducted a Weibull failure analysis using the data for pipes entering Repair Priorities 1 and 2, i.e., severely distressed pipes, fitting the two-parameter Weibull distribution shown in Eq. 1. Since, logically, it should take longer for a pipe to become severely distressed rather than simply distressed, only a 10-year incubation period was used in the analysis.

The plots in Figures 3 and 4 show the total number of distressed pipes measured by RFTC inspection, the fit Weibull distributions for the 10-year incubation period, and the accompanying failure rate curves for the CWS and WRSS, forecast to 2050.

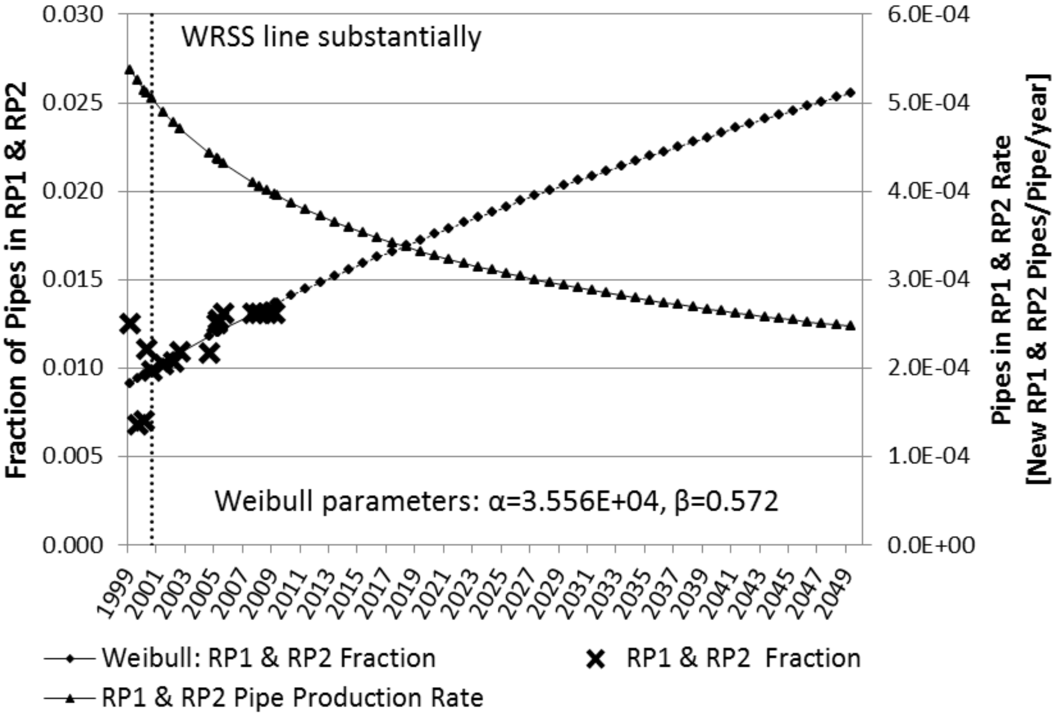

Figure 3. Prediction of new severely distressed pipes in WRSS based on a two-parameter Weibull distribution.

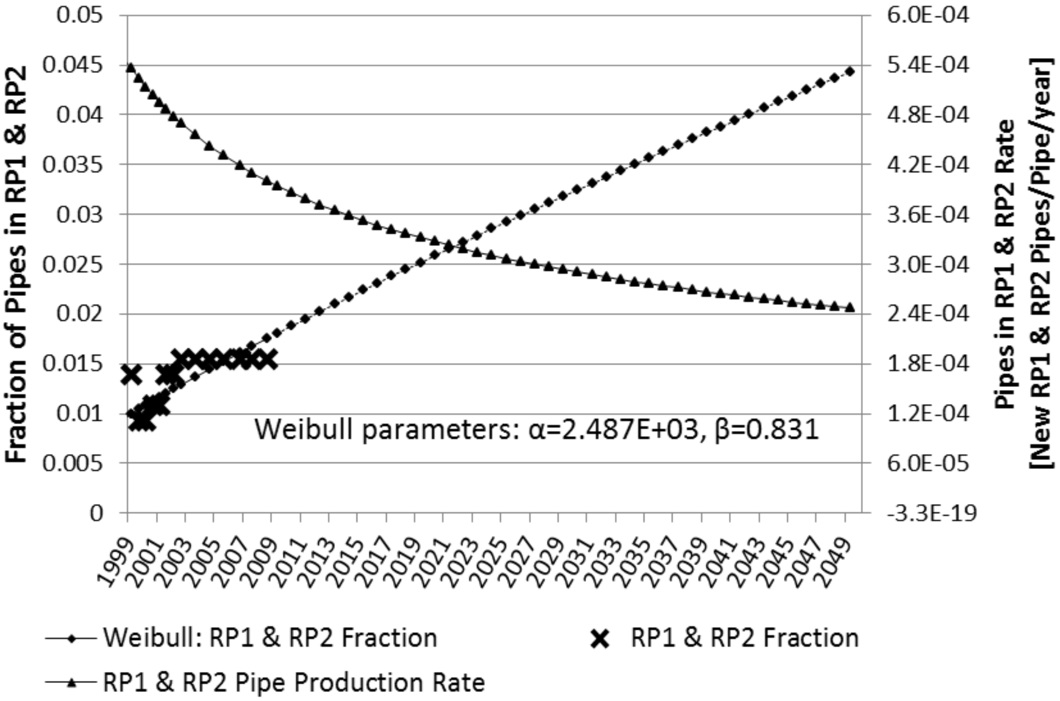

Figure 4. Prediction of new severly distressed pipes in CWS based on a two-parameter Weibull distribution.

Broken Wire Zone Growth

From the data tracking for the individual BWZs through the inspection history, we calculated the "short-term" BWZ growth rates, that is, those between consecutive inspections of the same BWZ. Having also assigned a Repair Priority to each BWZ at each inspection record, the short-term growth rate for a BWZ in each Repair Priority was determined.

Different probability distributions were fit to the data to characterize distress-dependent BWZ growth, including normal, log-normal, gamma, and Weibull distributions. The Weibull distribution, with BWZ growth rate as the random variable (t in Eq. 1), best fit the data. The distribution mean and standard deviation for BWZ growth at each Repair Priority for both systems is shown in Table 2. Results are discussed in the following section.

Table 2. Distribution mean and standard deviation of short-term BWZ growth (between consecutive inspection on unique BWZs).

Repair	WRSS			CWS		
Priority	Mean	StDev	No. Records	Mean	StDev	No. Records
All	0.77	1.49	1702	1.26	2.02	755
4	0.69	1.3	1365	1.35	2.24	598
3	1.14	2.19	256	1.00	1.42	156
2	0.99	2.31	81	NA	NA	1
1	NA	NA	0	NA	NA	0

DISCUSSION

Several important results are evident in the plots of distressed pipes in Figures 1 and 2. Whether a 0- or 10-year incubation period was selected, the distress rates are decreasing for both the CWS and WRSS. When a 10-year incubation period is assumed, both the forecast level of distress, and the forecast distress rate, are lower than when a 0-year incubation period is assumed, for both the CWS and WRSS. The plots show excellent agreement between the measured distress and the models with a 10-year incubation period.

The distress models with a 10-year incubation period predict that the distressed fraction of pipes in the WRSS will increase from 6.6% in 1999, to 8.4% in 2009, to 12.2% by 2050, as shown in Figure 1. The models also predict that the failure rate in the WRSS will decrease from 0.25% in 1999, to 0.16% in 2009, to 0.077% by 2050.

The distress models with a 10-year incubation period predict that the distressed fraction of pipes in the CWS will increase from 26.5% in 1999, to 36.5% in 2009, to 56.4% by 2050, as shown in Figure 2. The models also predict that the failure rate in the CWS will decrease from 1.8% in 1999, to 1.3% in 2009, to 0.74% by 2050.

The severe distress models predict that the severely distressed fraction of pipes in the WRSS will increase from 0.91% in 1999, to 1.3% in 2009, to 2.6% by 2050, as shown in Figure 3. The models also predict that the failure rate for severely distressed pipes in the WRSS will decrease from 5.4×10^{-4} in 1999, to 4.0×10^{-4} in 2009, to 2.5×10^{-4} by 2050.

The severe distress models predict that the severely distressed fraction of pipes in the CWS will increase from 0.96% in 1999, to 1.7% in 2009, to 4.4% by 2050, as shown in Figure 4. The models also predict that the failure rate in the CWS will decrease from 5.5×10^{-4} in 1999, to 1.0×10^{-4} in 2009, to 2.5×10^{-4} by 2050.

The plots of severe distress shown in Figures 3 and 4 predict a decreasing rate of pipes entering Repair Priorities 1 and 2, i.e., severely distressed pipes, for both the WRSS and CWS. The wider scatter in the data is likely due to there being far fewer pipes which develop severe distress. Also, many pipes at PVNGS are repaired before they develop severe distress.

The plots in Figures 2 and 4 include curves that indicate the date where the WRSS was substantially inspected. The distress level reported in the inspections prior to April 2001 covered portions of the WRSS with the highest distress, and are not representative of the system as whole. It is understandable that the areas with the highest distress were inspected first, since APS was aware of failure in these areas through their visual inspection and naturally inspected them first. To account for this, the failure analysis for the WRSS for both the level and severity of distress did not include data prior to April 2001.

The BWZ growth rate statistics in Table 2 do not show a statistically significant relationship between mean growth rate and Repair Priority for either the CWS or the WRSS. It should be noted that there are significantly more data for the lower Repair Priorities as compared with the more severe Repair Priorities. In fact, growth rate statistics are not avaialable for Repair Priority 1 in the WRSS, and Repair Priorities 1 and 2 in the CWS. The sparsity of data at the more severe Repair

Priorities is likely due to the effective repair program implemented at PVNGS. BWZ growth rate mean and standard deviation calculated here are within 15% and 35% respectively of growth rate statistics calculated for other similar pipelines we have investigated.

The high level of all-time distress in the CWS as compared to the WRSS (35.8% vs. 8.45% as of the most recent inspection in 2009) is likely due to the environment surrounding the pipes. Though both are cathodically protected, the CWS is essentially contained within the fenced area of the nuclear generating station, where stray currents are common, whereas the WRSS is a transmission line which passes through several residential neighborhoods and agricultural land.

CONCLUSIONS

This paper presents predictive statistical models for distress in PCCP assets. Starting from the detailed picture of current distress levels in the pipelines, the models forecast the progression of distress as total number of distressed pipes and total number of severely distressed pipes requiring repair or replacement through 2050. The statistical models were incorporated into the existing GIS for asset management purposes.

The study did not find a significant correlation between BWZ growth rate and distress level. The mean and standard deviation of BWZ growth rates found in this study are comparable to rates found in other similar pipelines. (Note that it was not possible to determine the growth rate of BWZ in Repair Priority 1, as pipes approaching this Repair Priority were repaired before distress could progress any further.)

The rate of new distressed pipe and the rate at which pipes enter Repair Priorities 1 and 2 (i.e., severly distressed pipe) decreases over the life of the pipeline.

The distress observed in PCCP at PVNGS is caused by corrosion of the prestressing wires. The methods and results presented here pertain to corrosion, and are not appropriate for hydrogen embrittlement driven by stray curent or high-voltages in the cathodic protection system.

Given the large body of inspection data available from utilities throughout the U.S. and abroad, the methods presented here are readily applicable and would be an invaluable tool for asset management, informing decisions related to repair or replacement of the individual PCCP or PCCP-line segments.

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