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RESEARCH ARTICLE

Evaluating the risk of water distribution system failure: A shared frailty model

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Abstract Condition assessment (CA) Modeling is drawing increasing interest as a technique that can assist in managing drinking water infrastructure. This paper develops a model based on the application of a Cox proportional hazard (PH)/shared frailty model and applies it to evaluating the risk of failure in drinking water networks using data from the Laramie Water Utility (located in Laramie, Wyoming, USA). Using the risk model a cost/benefit analysis incorporating the inspection value method (IVM), is used to assist in making improved repair, replacement and rehabilitation decisions for selected drinking water distribution system pipes. A separate model is developed to predict failures in prestressed concrete cylinder pipe (PCCP). Various currently available inspection technologies are presented and discussed.

Keywords condition assessment, risk, failure

1 Introduction

Drinking water asset management starts with accurate knowledge of the quality and quantity of the utility's treatment and distribution system components. The assessment of the treatment equipment is straight forward and can be evaluated by measuring performance and inspecting the maintenance paper work paper trail. The assessment of the distribution system is more complex since most of it is buried and unavailable to routine visual/physical inspection.

Drinking water utilities have becoming increasingly interested in the use of condition assessment modeling to manage their infrastructure assets. An important aspect of condition assessment modeling is the ability to quantitatively estimate the risks associated with the failure of distribution system pipe segments. Because of the national importance of this issue the USEPA initiated a project in collaboration with the Eastern Research Group to develop a quantitative risk model for drinking water infrastructure repair and replacement. The EPA has identified the repair, replacement and rehabilitation of distribution system assets as important economically and of vital importance to the nation's public health (Royer, 2005).

The project focused on four major aspects of drinking water infrastructure condition assessment and quantitative risk assessment. The first part of the project focused on the development of a quantitative statistically based risk model for pipe segment failure. The approach used in this effort was to combine a technique called frailty analysis with a Cox proportional hazards model (CPHM). The study team collaborated with the Laramie Wyoming water utility to quantify the risk of failure associated with individual pipe-sections, and complete pipe-lines or "runs", of steel, cast iron, ductile iron pipe (DIP) and PVC pipe and to identify the factors that influence these risks.

The second aspect of the project was the development of a model to quantitatively estimate the cost and benefits, including secondary and societal costs, of pipe repair, rehabilitation and replacement using an evaluation technique known as the inspection value method (IVM) (Brechling, 1995; Wall et al., 1998). This model was used to examine the advantages of using Inspection Technology as a means of anticipating needed replacement of pipe-run sections in an existing pipe line.

The third aspect of the study involved a separate assessment of prestressed cylindrical concrete pipe (PCCP). PCCP is of particular interest because it is frequently used to transmit large volumes of water and when failure occurs significant damage may result. In the 1960s and early 1970s, PCCP was commonly used and thought to be a solution to water related transmission/collection pipe problems. However, employment of large

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diameter PCCP has also increased the financial and product loss risks associated with pipe-line failure.

The fourth part of the project was the identification and assessment of the current state-of-the-art of pipe inspection technology. Various types of inspection technology have been used to identify storage tanks, pipes and pressure vessels that are beginning to fail due to corrosion or stress (Rajani and Kleiner, 2004). One such technique used in water and waste water networks is "Smart Ball" technology which is a self contained electromagnetic device that can roll along a pipe line and detect leaks and was used as part of an example.

2 Quantitative risk model

The model discussed in this section utilized data provided by the City of Laramie Wyoming Utility Division (Laramie Water) which provides the residents of Laramie with water and sewer services (Rogers, 2006). Pipe break data provided by the City of Laramie was analyzed using a CPHM modified by the use of frailty modeling. The CPHM and its application to pipe break modeling has been discussed extensively elsewhere (Clark et al., 2010). One of the limitations of the CPHM model is that it assumes a proportional fixed effect on the baseline hazard function and may fail to account for variability associated with unidentified factors that affect the pipe break process. To account for this unspecified variability "frailty" was incorporated into the modeling effort (Lam and Kuk, 1997). In survival analysis, a frailty is a positive random variable that is used to model individual (or group) multiplicative random effects on the hazard function. Frailty is defined to have an expected (mean) value of one so that it does not alter the conditional expected values from the model but introduces an additional element of random variation.

The Laramie data set contains information on individual pipe-sections as well as on pipe-runs or pipe-lines and therefore the first step in the analysis was the development of a model based on pipe-sections and then the pipe-section models were aggregated into pipe-run models. Analysis was limited to pipe diameters between 15.24 cm (6 inches) and 91.44 cm (36 inches) and to pipes installed after 1940 and later to try to get more consistency in the properties of the pipe. Individual pipe-run lengths varied from 0.305 m (1 foot) to 2816.7 m (9241 feet) (Clark et al., 2010).

2.1 Pipe section model

Risk models were developed for both metallic and PVC pipe are shown below. The metallic pipe model is expressed as follows.

$$h(t,\text{Material},\text{Diameter}) = \exp[7.53DIP + \text{Diameter}(-0.309 + 0.152DIP)]h_0(t)W_{\text{PipeID}}, \quad (1)$$

where $DIP = 0$ for Steel/CIP pipe or $DIP = 1$ for ductile iron pipe, Diameter = pipe diameter in inches, $h_0(t)$ is the baseline hazard function in breaks/year/pipe section, and W_{PipeID} is the shared frailty factor for all pipe-sections in the same pipe-run. W_{PipeID} takes on the value of random gamma variate with mean 1 and variance of 11.43 and $h(t$, Material, Diameter) is the hazard function in breaks/year/pipe section and t is years from installation.

Equation (1) can be used to provide the equation for ductile iron pipe ($DIP = 1$) as follows:

$$h(t,DIP,\text{Diameter}) = \exp[7.53 - 0.157\,\text{Diameter}]h_0(t)W_{\text{PipeID}}. \quad (2)$$

Equation (1) can also be used to provide the equation for steel/cast iron pipe ($DIP = 0$) as follows

$$h(t,\text{steel/castiron},\text{Diameter}) = \exp[-0.309\,\text{Diameter}]h_0(t)W_{\text{PipeID}}. \quad (3)$$

The PVC model is as follows:

$$h(t,PVC,\text{Diameter}) = \exp(-0.202\,\text{Diameter})h_0(t)W_{\text{PipeID}}. \quad (4)$$

The gamma variance for PVC is 0.94 and as indicated previously the gamma variance is 11.43. Therefore the variance of the PVC frailty is an order of magnitude less than that of the metallic pipe frailty. This would indicate that the PVC pipe is less subject to the local random external factors that impact the metallic pipes.

Figure 1 illustrates the application of Eq. (1) to 60.96 cm

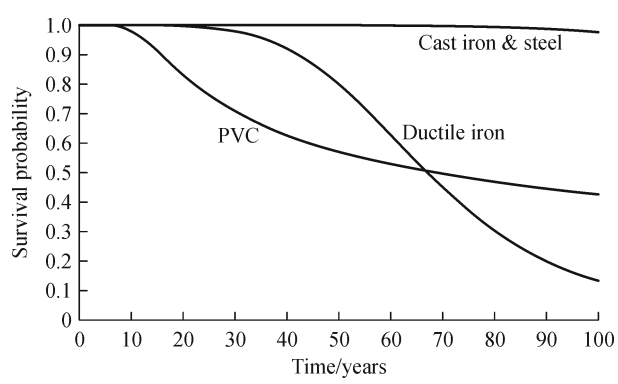

Fig. 1 Mean survival probabilities for 60.96 cm (24 inches) pipe-sections of ductile iron, cast iron, steel and PVC pipe sections

(24 inches) diameter pipe-sections. As can be seen the mean survival probabilities for steel and cast iron pipe-sections are identical but both PVC and DIP sections have shorter survival rates. It was found for Laramie that for all types of pipes, larger diameter pipes had better survival characteristics then smaller diameter pipes. Figure 2 illustrates the effect of diameter on survival probability for DIP-sections. Figures 3 and 4 illustrate the effect of frailty on both PVC and ductile iron pipe-sections. It can be seen that for DIP a small population (5%) of the pipe has a much shorter survival mean than an equivalent small population of PVC pipe. There are several implications that might be drawn from this analysis. One interpretation is that a fraction of the DIP is more vulnerable to unspecified environmental effects than PVC pipe. In addition it would appear that once DIP begins to break it may continue to break at a higher rate than PVC.

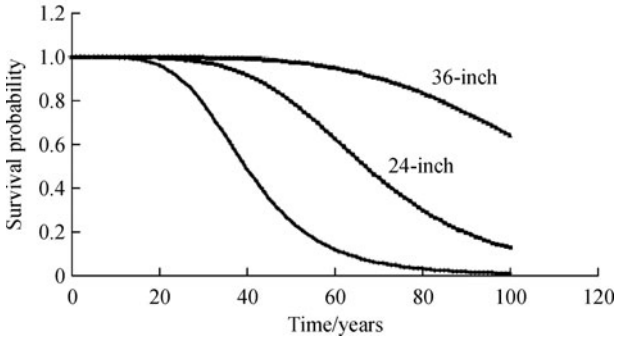

Fig. 2 Expected survival probabilities for 30.48 cm (12 inches), 60.96 cm (24 inches) and 91.44 cm (36 inches) diameter DIP-sections

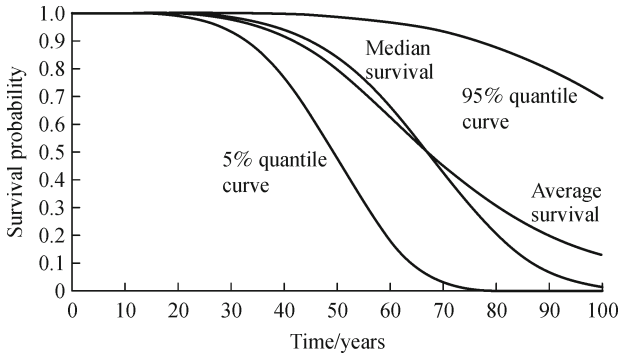

Fig. 3 Effect of frailty on mean survival rate for 60.96 cm (24 inches) PVC pipe-sections

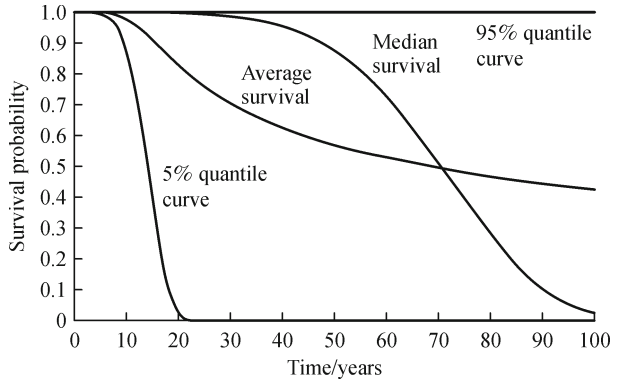

Fig. 4 Effect of frailty on mean survival rate for 60.96 cm (24 inches) DIP-sections

2.2 Cost/benefit analysis

The pipe section model was integrated into a pipe-run model and incorporated into a cost-benefit model yielding the following:

$$H_p(t) = k\int_0^t h_i(t)\mathrm{d}t, \tag{5}$$

where $H_p(t)$ is the cumulative hazard function for the pipe-sections and where $h_i(t) = h(t)$ or the hazard function for the individual sections discussed in the previous section and k is a the number of pipe-sections in a pipe-run or pipe line.

Therefore

$$S(t) = \mathrm{e}^{-H(t)}, \tag{6}$$

where $S(t)$ is the survival function. The survival function $S(t)$ is the probability of a pipe-section or pipe-run surviving beyond time t or equivalently the proportion of the population surviving beyond time t. For purposes of this analysis we will assume that the hazard function $h(t.\ z)$ is the modified CPHM proposed earlier.

The expected number of pipe breaks in a pipe-run at any given time, t is therefore given as follows:

$$E(t) = k[1 - S_p(t)], \tag{7}$$

where $E(t)$ is the expected number of breaks, for a pipe-run composed of k sections, at time t.

We can create a net value model as follows:

$$V = \left[\left(E(t)\times POD\times F\times FR\right) + \left(E(t)\times POD\times F\times SC\right)\right] - \left[\left(E(t)\times POD\times F\times R\right) + E(t)\times(1-POD)\times F \times(FR+SC)+AIC)\right], \tag{8}$$

where,

V = the added value added due to inspection;

AIC = the annual cost of applying the inspection technology;

$E(t)$ = expected number of breaks, for a pipe-run at time t;

F = the coverage;

FR = the cost of forced repair;

POD = the probability of detecting a failure (technology specific);

R = the preemptive cost of repair identified by the application of inspection technology;

SC = the cost to society of water loss and other indirect costs.

To illustrate the application of the cost/benefit model we assume, a 2133.6 m (7000 feet), 60.96 cm (24 inches) DIP pipe-run, similar to the example discussed in Clark et al. (2002) consisting of 6.1 m (35020 feet) pipe sections. Using the model from Clark et al. (2002) the pipe-run replacement cost was calculated as $1120000 ($3200 per pipe section). The producers price index (http://data.bls.gov/PDQ/servlet/SurveyOutputServlet) was used to upgrade these costs to current costs (2008). These data yielded a current total replacement cost for a 2133.6 m (7000 feet) DIP pipe-run, 60.96 cm (24 inches) in diameter as $1568000. It is assumed, therefore, that it will cost $4480 to replace a single section of 60.96 cm (24 inches) DIP pipe. Based on earlier work on inspection technologies, it was assumed that the inspection technology cost would cost $20000/mile/year so that for a 2133.6 m (7000 feet) pipe the inspection cost is estimated as $30000 per year. If a break actually occurs, it is assumed two sections of pipe are replaced so the repair cost for a 60.96 cm (24 inches) DIP pipe is $8960. It is further assumed that if a pipe section does not break but is identified by the inspection technology device as a candidate for replacement then only one section of pipe is assumed replaced.

Figure 5 illustrates the application of Eq. (5). It shows the relationship between the inspection benefit versus the cost of inspection for a 60.96 cm (24 inches) DIP versus time. As can be seen for the first ten years the costs exceed benefits but after 15 years the application of the inspection technology yields a positive benefit. Analysis shows the largest gains are derived by the larger diameter pipes. A possible asset management strategy might be to delay the start of inspection until the benefits are clear. Analysis of 30.48 cm (12 inches) and 91.44 cm (36 inches) diameter pipe indicate that benefits increase dramatically with diameter. Although this analysis, based on the data compiled by the Laramie Water Utility, shows a positive benefit for the inspection technology selected results might be dramatically different for another type of device or material.

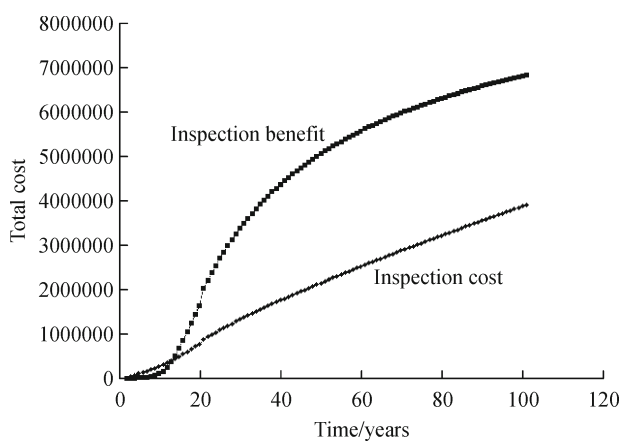

Fig. 5 Inspection benefit and inspection cost versus years for 60.96 cm (24 inches) diameter DIP-run

3 PCCP analysis

In a recent survey, the USEPA (2007) found that of the 202128 miles of distribution system pipes reported, 4774 (2.3%) were PCCP. If that number is extrapolated on a National basis, about 1000000 miles of pipe are in service, with about 23600 miles of PCCP. PCCP is of particular interest because it is frequently used to transmit large volumes of water and failure results in significant damage. In the 1960s and early 1970s, PCCPs were commonly used and thought to be the solution to the water related transmission/collection pipe problems. However, employment of large diameter PCCPs also increased the financial and product loss risks associated with their failure. Several catastrophic drinking water transmission line ruptures illustrate this problem (Higgins et al., 2007; Galleher et al., 2007; Padewski at al., 2007). In 2006, The San Diego Water Authority quickly responded to a rupture in a 243.84 cm (96 inches) line (Galleher et al., 2007). Even with a rapid response, an estimated 2000000 gallons of water were lost before the break was brought under control. When the direct and indirect repair costs associated with this break were totaled, several millions of dollars were spent repairing this break. Reducing the failure risk by knowing the breakage probabilities of large diameter pipes can facilitate targeted maintenance, reduce costs and allow more efficient use of existing and future assets.

A comprehensive data set for large diameter PCCPs was identified and was used for the analysis of PCCP breakage rates in this paper. The database used in this paper contained 588 entries from 153 utilities and included maintenance information such as: diameter, pipe type (LC or EC), wire class, wire size, age at ruptures, and other failures, failure condition, length, pressure, and manufacturer. There were 31 different pipe diameters represented in the database that ranged from 40.64 to 640.08 cm (16 to 252 inches). The database was examined for specific pipelines that had multiple maintenance activities over time. The pipelines found that met this requirement were 60.96, 76.20, 94.11, 121.92, 152.4, 182.88, 213.36, 228.60 and 243.84 cm (24, 30, 36, 48, 60, 72, 84, 90 and 96 inches) in diameter. From each of the diameters at least one pipeline was selected for analysis. In total, 15 pipelines were selected. The 15 different pipelines yielded two hundred and 26 individual maintenance activities representing over 112 service observations. A regression analysis was chosen to determine if there was a statistical

significance between the variables: age, diameter, pipe type and the breakage rate per mile. Of the three, diameter and age were the only statistically significant variables.

Previously completed research indicated that pipe characteristics of diameter and age were exponentially related to break rate per mile. It was proposed that the significant PCCP variables of diameter and age also be examined as an exponential relationship. The general equation proposed was

$$Y = (\text{Diameter})^{a} \times (\text{Age})^{b}. \quad (9)$$

The exponential model was regressed through the origin and resulted in the following equation.

$$Y = (\text{Diameter})^{-0.90} \times (\text{Age})^{1.1},\ R^2 = 0.60. \quad (10)$$

Analysis of the variances in the standard error indicated that diameter and age were statistically significant and as indicated by the parameter exponents decreased with diameter and increased with age. Since this was a national summary of maintenance data from many different geographical areas, there was considerable scatter in the data. With an R^2 value of 0.60, the analysis is only correlating about 60% of the variables diameter and age with the PCCP break rate. While age and diameter are probably the most important variables, there is still a considerable amount of work required on this subject before the PCCP break rates can be correlated with a high degree of confidence.

Using Eq. (9), the individual relationships between break rate per mile for diameter and age can be calculated. The results of those calculations are shown in Figs. 6 and 7.

The analysis of the PCCP database for a relationship between breaks per mile and age indicates that large diameter pipes fail more frequently as they age and less frequently with larger diameters. This is not totally news but helps to define a mathematical description of two of the variables affecting the performance of PCCPs.

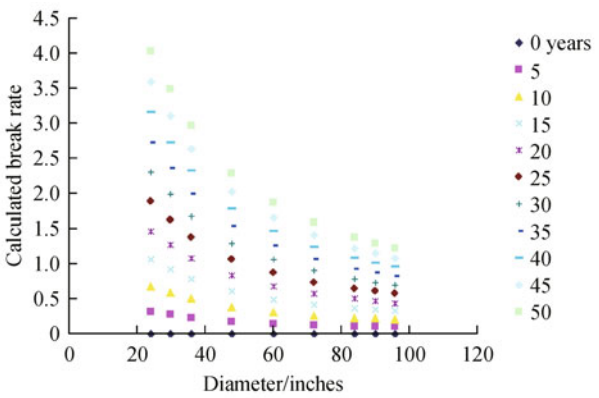

Fig. 6 Predicted break rate per mile with diameter

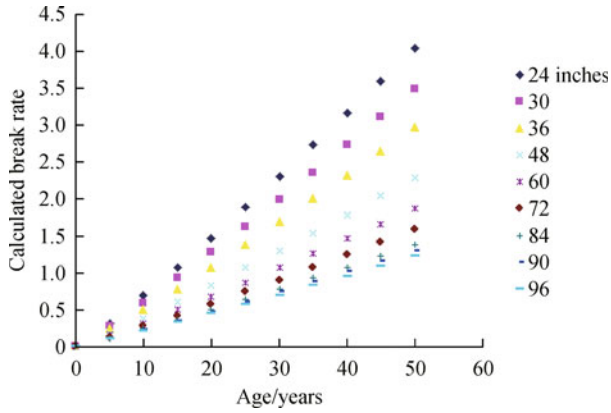

Fig. 7 Predicted break rate per mile with age

4 Inspection technologies

Drinking water asset management starts with accurate knowledge of the quality and quantity of the utility's treatment and distribution system components. The assessment of the treatment equipment is straight forward and can be evaluated by measuring performance and inspecting the maintenance paper work paper trail. The assessment of the distribution system is more complex since most of it is buried and unavailable to routine visual/physical inspection.

Condition assessment is the ability to collect and convert inspection results into a realistic estimate of a pipeline's fitness-for-service for a given period of time. Condition assessment technologies are the procedures, devices and systems used to collect and analyze the inspection results. The application of this approach to asset management of drinking water distribution pipes would be a major step forward in reducing the financial gap by properly allocating resources to distribution system areas that need immediate attention and evaluate the risks associated with minimizing maintenance on distribution system pipes that are not in danger of failure.

To actively engage in a condition assessment program of distribution system mains, utilities need access to technologies that provide that function, and are:

- Non-disruptive to normal service
- Accurate and reliable
- Affordable.

A summary of the currently available inspection technologies and their application to various pipeline components is presented in Table 1. This summary is not definitive in that all of the information for the data gaps is not known or reserved as confidential business information. As the inspection techniques continue to develop and their applications are expanded the data gaps will gradually fill in.

Table 1 Currently available inspection technologies

Technology	Vendor	Pipe type
Acoustic emission monitoring	Infrastructure management technologies, pure technologies	PCCP
Acoustic leak detection	WRc, AccuCorr digital, Sound sense logging correltors	All
Acoustical leak detection/digital correlator	Flow matrix	All
Acoustical monitoring soundprint	Pure technologies	PCCP
Broadband electromagnetic		Steel
Closed circuit TV	Many non proprietary technologies	All
Electromagnetic inspection	Pure technologies (P wave)	
Long range ultrasonic		Steel
Magnetic flux leakage	CSIRO manufacturing and infrastructure technology	Steel, cast iron and ductile iron
Remote field eddy current	Off the shelf, testEx, Russell technologies/hydroscope	Steel, cast iron and ductile iron
Remote field transformer coupling	Pressure Pipe Inspection Co (PPIC)	PCCP
Sahara leak detection	PPIC, pure technologies	PPCP
Transient pressure monitoring	Pipetech international	All
Ultrasonic	NCD corp	PCCP, asbestos cement

5 Conclusions

In this paper a model incorporating CPHM with shared frailty (by pipe-section) for metallic and PVC pipe has been developed in order to estimate the risk of pipe breaks. The Inspection Value Method (incorporating the CPHM) has been applied to the Laramie pipe-run data based on a hypothetical 69.96 cm (24 inches) DIP example to illustrate the relative costs and benefits of using inspection technology. A separate pipe break analysis was conducted for PCCP and it was discovered that larger diameter pipe had lower break rates than smaller diameter pipes. Various inspection technologies were examined and evaluated and found to be promising.

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References

Brechling V J (1995). A Methodology for the Economic Assessment of Nondestructive Evaluation Techniques Used in Aircraft Inspection. Report No. DOT/FAA/AR-95/101 National Technical Information Service (NTIS), Springfield, USA

Clark R M, Carson J H, Thurnau R C, Krishnan E R, Panguluri S (2010). Condition assessment modeling for distribution systems using shared frailty analysis. JAWWA, 7(102): 81–91

Clark R M, Sivaganesan M, Selvakumar A, Sethi V (2002). Costs models for water supply distribution systems. J Water Resour Plan Manage, 128 (5): 312–321

Galleher J J, Holley M, Shenkiryk M, Eaton G (2007). Snap, crack, pop—Recording of a prestressed pipe failure. Advances and Experiences in with Trenchless Projects, ASCE, 1–9

Higgins M S, Gadoury, Razza R, Mead I (2007). Technologies to assess and manage providence's water's 102 inch PCCP aqueduct. Advances and Experiences with Trenchless Projects, ASCE, 1–8

Lam K F, Kuk A Y C (1997). A marginal likelihood approach to estimation in frailty models. J Am Stat Assoc, 439 (92): 985–990

Padewski E, Leshner N, Woodcock M, Higgins M (2007). Assessing PCCP Transmission Mains. Pipelines Specialty Conference, ASCE, 1–6

Rajani B, Kleiner Y (2004). Non-destructive Techniques to Determine Structural Distress Indicators in Water Mains. In: Evaluation and Control of Water Loss in Urban Networks, Valencia, Spain, June 21–25, 1–20

Rogers P D (2006). Failure assessment model to prioritize pipe replacement in water utility asset management. A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy, Colorado State University

Royer M D (2005). White paper on improvement of structural integrity monitoring for drinking water mains. National Risk Management Research Laboratory, Office of Research and Development, USEPA, Cincinnati, USA

USEPA (2007). Distribution System Inventory, Integrity and Water Quality. Office of Water, Washington DC, USA

Wall M, Wedgewood F A, Martens W (1998). Economic assessment of inspection—The inspection value method. NDT.net, 3(12)