Evaluating the Risks of Water Distribution System Failure

Effective asset management starts with accurate knowledge of system components. Condition assessment modeling is helping utilities forecast distribution system frailties. **By Robert M. Clark and Robert C. Thurnau**

**PROJECT SCOPE**

The project focused on four aspects of drinking water infrastructure condition and quantitative risk assessment. The first part of the project focused on developing a quantitative, statistically based risk model for pipe-segment failure. The idea was to combine a technique called frailty analysis with a Cox Proportional Hazards Model (CPHM). The study team collaborated with the Laramie (Wyo.) Utility Division (Laramie Water) to quantify the risk of failure associated with individual pipe sections and complete pipelines or runs of steel, cast-iron, ductile-iron, and polyvinyl chloride (PVC) pipe and to identify factors influencing the risks.

The second aspect of the project was to develop a model for estimating costs and benefits, including secondary and societal costs, of pipe repair, rehabilitation, and replacement using the Inspection Value Method evaluation technique. The model was used to examine the advantages of using inspection technology to anticipate needed replacement of pipe-run sections.
The third aspect of the study assessed prestressed cylindrical concrete pipe (PCCP), which is of particular interest because it’s frequently the means of transmitting large volumes of water. Therefore, when failure occurs, significant damage likely results. Commonly used in the 1960s and early 1970s, PCCP was thought to solve water-related transmission and collection pipe problems. However, use of large-diameter PCCP has led to increased financial and product-loss risks associated with pipeline failure.

The fourth part of the project was to identify and assess current, state-of-the-art pipe inspection technology. Various types of inspection technology have been used to identify failure caused by corrosion or stress in storage tanks, pipes, and pressure vessels. To conduct a CA of distribution system mains, utilities must have access to technologies that are nondisruptive to normal service, accurate and reliable, and affordable. A summary of currently available inspection technologies and their application to various pipeline components is presented in the table at left.

One such technique used in water and wastewater networks is a self-contained electromagnetic device that rolls along a pipeline to detect leaks. The device was used as part of the cost–benefit analysis.

**QUANTITATIVE RISK MODEL**

The model used data provided by Laramie Water, which provides water and sewer services to Laramie residents. Pipe-break data provided by the city of Laramie were analyzed using the CPHM, which was modified by use of frailty modeling. Frailty analysis is a technique used by medical epidemiologists to identify subpopulations with a common susceptibility to a disease or weakness. In terms of pipe failure, this means identifying a group of pipes that seem to be especially susceptible to failure from specific causes. Frailty is defined as having an expected (mean) value of one, so it doesn’t alter conditional expected values from the model but provides an estimate of random factors that might influence pipe breaks.

The Laramie dataset contains information about individual pipe sections, pipe runs, and pipelines. Therefore, the first step was to develop a model based on pipe sections. Next, the models were aggregated into pipe-run models. Analysis was limited to pipe diameters between 6 in. and 36 in. and to pipes installed after 1940. Individual pipe-run lengths varied from 1 ft to 9,241 ft.

**Pipe Section Model.** Risk models were developed for metallic and PVC pipe. According to the model, the frailty variance for PVC pipe and metallic pipe was determined to be 0.94 and 11.43, respectively. Therefore, the PVC frailty variance is an order of magnitude less than the metallic pipe frailty, which means that PVC pipe is much less susceptible to local random external...
factors than those that affect metallic pipes.

Figure 1 illustrates applying the model to 24-in.-diameter pipe sections. The mean survival probabilities for steel and cast-iron pipe sections are identical, but PVC and ductile-iron pipe (DIP) sections have shorter survival rates. In Laramie, larger-diameter pipes of all types had better survival characteristics than smaller-diameter pipes.

Figure 2 illustrates the effect of diameter on survival probability for DIP sections. The same pattern was also typical for other types of pipe. Figure 3 illustrates the effect of frailty on PVC and DIP sections. For DIP, 5 percent of the pipe had a much shorter survival rate than an equivalent population of PVC pipe. Several implications can be drawn from this analysis. One interpretation is that a fraction of DIP is more vulnerable to unspecified environmental effects than PVC pipe. In addition, it appears that, when DIP begins to break, it may continue to break at a faster rate than PVC.

Cost–Benefit Analysis. The pipe-section model was integrated into a pipe-run model and incorporated into a cost–benefit model. Following is an example:

Assume a 7,000-ft, 24-in. DIP pipe run consisting of 350 sections of 20-ft pipe. Using the model, the pipe-run replacement cost was calculated to be $1.12 million ($3,200 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 the described DIP pipe run of $1,568,000. Therefore, it’s assumed that replacing a single section will cost $4,480 and the inspection technology cost would be $20,000/mile/year. So, for a 7,000-ft pipe, the inspection cost is estimated at $30,000/yr. If a break actually occurs, it’s assumed that two sections of pipe would need to be replaced, so the repair cost for a 24-in. DIP pipe would be $8,960. It’s further assumed that, if a pipe section doesn’t break but is identified by the inspection technology device as a candidate for replacement, only one section of pipe is assumed to be replaced.

A cost–benefit model was developed that includes the following factors:

\[ V = \text{value added by the inspection} \]
\[ AIC = \text{annual cost of applying the inspection technology} \]
\[ C = \text{total cost of inspection, including all direct and indirect costs associated with restoration} \]
\[ E(t) = \text{expected number of breaks for a pipe-run at time } t \]
\[ F = \text{percentage of the pipe covered} \]
\[ FR = \text{cost of forced repair} \]
\[ POD = \text{probability of detecting a failure (technology specific)} \]
\[ R = \text{preemptive cost of repair identified by the application of inspection technology} \]
The study shows that large-diameter pipes fail less frequently than smaller-diameter pipes, and all pipes fail more frequently with age.

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

\[ V = \left[ (E(t) \times POD \times F \times FR) + (E(t) \times POD \times F \times SC) \right] - \left[ (E(t) \times POD \times F \times R) + E(t) \times (1 - POD) \times F \times (FR + SC + AIC) \right] \]

Illustrating the cost–benefit model, Figure 4 shows the relationship between the benefit and the cost of inspection for a 24-in. ductile iron pipe over time. For the first 10 years, costs exceed benefits. However, after 15 years, the use of inspection technology yields a positive benefit. Analysis shows the largest gains are derived from larger-diameter pipes. A possible asset management strategy might be to delay inspection until the benefits are clear. Analysis of 12-in.- and 36-in.-diameter pipe indicates benefits increase dramatically with diameter. Although this analysis, based on data compiled by Laramie Water, shows a positive benefit for inspection technology, selected results might be dramatically different for another type of device or material.

**PCCP ANALYSIS**

In a recent survey, USEPA found that, of 202,128 mi of reported distribution system pipes, 4,774 mi (2.3 percent) were PCCP. If that number is extrapolated on a national basis, it’s estimated that about 1 million mi of pipe are in service, of which 23,000 miles are PCCP. Use of large-diameter PCCPs increased the financial and product-loss risks associated with failure. Some catastrophic drinking water transmission line ruptures have illustrated this problem. For example, in 2006, the San Diego Water Authority responded quickly to a ruptured 96-in. line. Although response was rapid, an estimated 2 mil gal of water were lost before the break was brought under control. When direct and indirect repair costs of the break were totaled, several millions of dollars were spent in repairs. 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.

The database was examined for specific pipelines that had undergone multiple maintenance activities over time. The pipelines that met this requirement were 24 in., 30 in., 36 in., 48 in., 60 in., 72 in., 84 in., 90 in., and 96 in. in diameter. At least one pipeline was selected for analysis from each of the diameters. A total of 15 pipelines was selected, which yielded 226 individual maintenance activities, representing more than 112 service observations. A regression analysis determined that, of the three variables studied affecting breakage rate/mi, only age and diameter were significant.
Break rate decreased with diameter and increased with age. Although age and diameter are probably the most important variables, considerable work is required before PCCP break rates can be correlated with a high degree of confidence. The results of those calculations are shown in Figure 5.

The study shows that large-diameter pipes fail less frequently than smaller-diameter pipes, and all pipes fail more frequently with age.

**STUDY RESULTS PROMISING**

In summary, a model incorporating CPHM with shared frailty (by pipe section) for metallic and PVC pipe was developed to estimate pipe-break risks. The Inspection Value method, which incorporated CPHM, was applied to Laramie Water's pipeline data based on a hypothetical 24-in. DIP to illustrate relative costs and benefits of using inspection technology. A separate pipe-break analysis for PCCP revealed that larger-diameter PCCP had lower break rates than smaller-diameter PCCP pipes. Various inspection technologies were examined, evaluated, and found to be promising.

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