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Tarrant Regional Water District's Risk Management Plan for Prestressed Concrete Cylinder Pipe

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Abstract

The Tarrant Regional Water District (TRWD) operates two, 120 km long, large diameter prestressed concrete cylinder pipelines in north central Texas to daily supply water to over 1.5 million people. Both pipelines have suffered from failures due to corrosion, hydrogen embrittlement or inadequate thrust restraint, with about 800 pipe segments damaged. A model was developed to determine remaining strength of the damaged pipe. About 100 pipe segments, most of which have been replaced, were found to be damaged enough that they could fail and about 250 more were found to be damaged enough that further deterioration would put them at risk of failure. To prioritize their replacement, the District will use a fuzzy risk model. TRWD is attempting to balance the high cost of mitigating all damaged pipes with the potential cost of consequential damages due to a failure by modeling the risk. This paper will discuss the path TRWD is taking to further its model development of risk management of the pipeline.

Introduction

The Tarrant regional Water District is a raw water supplier in North Central Texas, serving communities in ten counties, including Fort Worth and surrounding communities. The District has twenty-six municipal customers who supply treated water to about 1.5 million people. Water use in Tarrant County is about 92% of the District's total use. The District's supply, shown in figure 1, consists of four supply reservoirs, two pipelines and two pipeline terminal storage reservoirs. The two western reservoirs, Bridgeport and Eagle Mountain hold about twenty percent of the total supply, and release water down the Trinity River to Tarrant County. Water

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from Cedar Creek is pumped using a 183 cm (72-inch) diameter, 109 km (sixty-eight mile) long pipeline and an 213 cm (84-inch) diameter 10 km (six-mile) long pipeline to Tarrant County. Water is pumped from Richland Chambers in a 229 cm (90-inch) diameter 116 km (seventy-two mile) long pipeline and a 274 cm (108-inch) diameter 10 km (six-mile) long pipeline to Tarrant County. Lakes Arlington and Benbrook serve as terminal storage reservoirs for the pipeline. Water from Lake Benbrook can be pumped into the pipeline system to serve the Tarrant County water treatment plants. Since Cedar Creek and Richland Chambers Reservoirs are eighty percent of the water supply, the reliability of the pipelines is essential.

Figure 1. Map of the TRWD System

Pipeline Integrity Issues

The Cedar Creek Pipeline was constructed in 1972. The pipeline has suffered nine failures, the first in 1981. Eight of the nine failures have been due to corrosion of the prestressing wires. One failure has been due to hydrogen embrittlement damage. All have been catastrophic failures, with a large section of the pipe being failing resulting in the loss of millions of gallons of water. One area of the Cedar Creek Pipeline was under an impressed current cathodic protection system. The hydrogen embrittlement segment that failed was connected to the rectifier. The Richland Pipeline was constructed in 1988. The Richland pipeline has suffered thirteen failures: four thrust restraint failures, six corrosion failures, one due to hydrogen embrittlement, one from a spigot cracking, and one from operator error. All but the

thrust restraint and spigot cracking was catastrophic failures. Richland Chambers had no cathodic protection, and the embrittled segment was probably due to the wire characteristics being influenced by light surface corrosion of the wire.

The District recognized in 1989 that the pipe integrity was deteriorating and began to study and mitigate the problems. The entire system was cathodically protected using sacrificial zinc anodes to stop corrosion damage while minimizing further embrittlement damage. Water hammer was identified as a possible cause of cracking the outer mortar and mitigated by using programmable logic controllers on the pump control valves to prevent premature closing. The pipelines were also internally inspected and obvious damaged segments repaired or replaced. Beginning in 1998, the District employed the Pressure Pipe Inspection Company (PPIC) to inspect the pipeline using the remote field eddy current/coupled transformer system. About 32 km have been inspected annually and in January 2005 the inspection was complete for both pipelines.

PPIC's inspections are internal inspections, requiring the pipe to be dewatered. They use an inspection tool utilizing remote field eddy current / transformer coupling technology. PPIC's remote field eddy current / transformer coupling technology functions much in the same way as a radio transmitter and receiver. The "transmitter" produces an electromagnetic field. The prestressing wires in the pipe amplify the signal. If there are broken pre-stressing wires, the signal does not come through cleanly and our "receiver" picks up static, or noise.

Results of the PPIC inspections revealed that of the 37148 segments inspected, 818 segments have wire breaks. The Cedar Creek Pipeline has about four percent of the segments damaged, a total of 718 segments. The inspection of the Cedar Creek pipeline near the rectifier location revealed about nine percent of the pipe was damaged, likely due to embrittlement. The Richland line has about 0.5 percent of the segments damaged, a total of 100 segments. Of those 818 damaged segments, about 70 have been replaced or repaired. Repairs were done the follow winter of the inspecting, generally choosing the pipe with 50 or more broken wires. The first repairs of the embrittled area revealed that although the pipe may be damaged with 100 broken wires, the force required to crush the pipe for removal demonstrated that the pipe had high residual strength. Embrittled pipe was then replaced when over 125 broken wires were detected in subsequent work.

Modeling for Remaining Strength

During the initial investigation of the pipeline integrity problems, the District contacted other agencies that were facing similar issues. The San Diego County Water Authority had been investigating their problems and aided the District in our efforts. The Bureau of Reclamation organized a meeting in the mid 1990s of agencies with problems, the "Prestressed Concrete Pipe User's Group" and met to discuss issues and solutions. The group continued to periodically meet and a number of agencies jointly funded a study by Simpson Gumpertz & Heger (SGH) to develop

a simplified finite element analysis to determine residual strength of damaged pipe. The District employed SGH to examine the pipe designs specific to the District, develop and calibrate the model for embrittlement damage and determine the residual strength and repair priorities for the damaged pipe.

A simplified strength model was developed to examine the impact of adjacent corroded and failed prestressing wire on the remaining strength of the pipe. Since prestressed concrete cylinder pipe is a composite pipe, each structural element adds to the strength. When the prestressing wire fails, additional tensile stress is transferred to the adjacent wires, the concrete core and the steel cylinder. Indications of deterioration are first microcracking in the concrete core then visible cracking in the core. As the number of prestressing wires that fails increases, the tensile stress increases on the steel cylinder until it exceeds its elastic limit and fails. At that time the pipe catastrophically fails.

The model is also used to examine the relationship between two damage zones and defined when those two zones were close enough to be combined into a single zone. The model also estimates the remaining strength through time, given an estimate of the rate of continued damage. With the model, the corrosion damaged pipe could be prioritized for current conditions and for future conditions.

SGH continued to refine the model to estimate the remaining strength of pipe damaged by hydrogen embrittlement. Several embrittlement damaged pipes were tested to failure to calibrate the model. With the model calibrated, SGH applied the model to the inspection information from the Cedar Creek pipeline to prioritize the embrittled damaged pipe.

The simplified strength model categorized the damaged pipe into four priority levels. Priority level 1 was pipe that had enough damage such that the segment's highest anticipated operating load exceeded the remaining strength and catastrophic failure was possible. Priority 2 pipes had damage significant enough that the remaining strength of the pipe could still withstand the maximum operating load, but further deterioration of the wire or cylinder would result in failure. Priority 3 pipes had damage to the point where the core would crack, exposing the steel cylinder to possible corrosion. Priority 4 pipes had limited damage with no core cracking.

The results of the strength model shows that embrittled pipe has a much higher remaining strength compared to corroded pipe segments. The two graphs below, figures 2 and 3, show the strength model results for a 183 cm (72 inch) diameter 10 bar (150 psi) pressure class pipe designed for 183 cm (six feet) of cover. The embrittlement damaged pipe is able to withstand a great deal more damage and pressure and still stay safely in service.

Based on the study results, the District's choice of segment replacement has covered almost all the segments in eminent danger of failure, the priority 1 pipe segments.

Figure 2. Risk curves for a corrosion damaged pipe

Figure 3. Risk curves for an embrittlement damaged pipe

There still remain a large number of pipes that, with continued deterioration will fail, the priority 2 pipe segments. There are also a large number of pipes with limited damage that may remain in service (priority 3 and 4).

The study incorporates uncertainty in the analysis, including inspection error, degraded adjacent wires, the continued rate of deterioration and the interaction of two or more broken wire zones in the same segment of pipe. The study recommended:

1. Develop the potential transient wave pressures that the pipe segments may experience and reevaluate the risk to the damaged pipes
2. Repair all Priority 1 pipes and plan to repair all priority 2 pipes within a reasonable period
3. Develop a database of electromagnetic and visual inspections
4. Perform subsequent electromagnetic reinspections to better define the progress of deterioration.

The District had a reinspection of nine miles of the Richland line in January, 2005. Results showed some segments had no further deterioration, while some segments continued to deteriorate. No clear trend was noted. The District, in response to the recommendations, is also having the transient pressures evaluated. The District has also begun discussions with PPIC to examine the confidence in the data interpretation of the inspection for the pipes in the priority 2 strength group. This, along with a better defined rate of deterioration, will help in prioritization of segment replacement.

Fuzzy Risk Modeling

The District is also participating in an American Water Works Research Foundation study with the National Research Council Canada. The study is developing a fuzzy Markov deterioration process model to manage the risk in large water transmission mains. Fuzzy-based techniques seem to be particularly suited to modeling the deterioration of infrastructure assets for which data are scarce and cause-effect knowledge is imprecise. The Markovian deterioration process requires that the condition of the deteriorating system be encoded as an ordinal condition state. The condition assessment of a large buried pipe comprises two steps. The first step involves inspection of the pipe using direct observation (visual, video) and/or non-destructive evaluation (NDE) techniques (radar, sonar, ultrasound, sound emissions, eddy currents, etc.), which reveal distress indicators. The second step involves interpretation of these distress indicators to determine the condition state of the pipe. This interpretation process is dependent upon the inspection technique. The interpretation of the visual inspection results, although based on strict guidelines, can often be influenced by subjective judgment. The interpretation of NDE results on the other hand, is often complex (at times proprietary) and imprecise. Fuzzy-based techniques seem therefore uniquely suited to addressing this encoding process as well.

Kleiner *et al.* (2004a) introduced a new approach to modeling the deterioration of buried pipes, using a fuzzy rule-based, non-homogeneous Markov process. This deterioration model yields the possibility (as opposed to probability) of failure at every point along the life of the pipe. Kleiner *et al.* (2004b) expanded this approach by expressing the possibility of failure, as a fuzzy number, and then coupled it with the failure consequence (also expressed as a fuzzy number) to obtain the failure risk as a function of pipe age. Kleiner *et al.* (2004c) expanded the approach further, to include methods to assess post-renewal deterioration rate and subsequently make rational decisions on when to schedule the subsequent condition assessment of a pipe, when to renew a deteriorated pipe, and how to select the most economical renewal alternative, assuming it is technically feasible and appropriate.

With the fuzzy Markov approach, failure risk can be modeled as a fuzzy band throughout the life of the pipe (see figure 4). This fuzzy risk band can be bounded by an upper (conservative) and lower (optimistic) possibility bounds that are the possibilistic equivalent of confidence bands in the probabilistic world. If a utility knows its own risk tolerance, it can make a clear decision when to schedule a pipe inspection/condition assessment.

Figure 4: Fuzzy risk levels over the life of a pipe (after Kleiner et al. 2004c)

Continued Model Development

The task ahead is to prioritize the damaged pipe for replacement and to estimate when these pipes will need to be replaced. The first step is to classify the damage as corrosion or embrittlement. Pipe segments that cannot be easily classified will be treated as corroded until they can be excavated and examined. The SGH model will

be the tool used to rank the pipe into the four priority categories for current conditions and for estimated conditions in five years. Any current priority 1 pipes that have not been replaced will be as soon as possible. All priority 1 pipes for the five-year condition will be flagged as high priority replacements. Priority 2 pipes will be analyzed further to rank the priority and timing of replacement. There are between two to three hundred priority 2 damaged pipes that will be analyzed.

The priority 2 pipes will be ranked by incorporating a number of elements in a fuzzy risk model. The elements included in the fuzzy risk model include:

Parameters affecting the rate of deterioration:

- Maximum pressure/pressure class may indicate pipe that are at their design limit
- Soil chemistry: soil resistivity, chlorides and sulfates may affect the rate of deterioration
- Construction without shorting straps: Seventeen miles of the Cedar Creek Pipeline does not have shorting straps, limiting the effectiveness of cathodic protection

Parameters affecting repair time:

- Accessibility: some damaged segments are in flood plains, which may be inaccessible for weeks due to flooding. Other segments may be far from any roadways
- Time to dewater: certain areas of the pipeline are very flat and require almost a week to dewater so segment replacement may begin.

The consequences of failure:

- Consequential damages: land use in the immediate area of damaged segments and distance from structures

There are several hundred segments of pipe that have enough damage to warrant concern spread throughout the two pipelines. The District's approach to pipeline integrity is to mitigate any continued deterioration and replace the segments when they pose a risk for failure. The cost to repair or replace a single segment varies from about \$35,000 to \$75,000. Using \$40,000 as an average cost for replacement, replacing 300 pipe segments could cost at least \$12,000,000. By taking the approach of predictive maintenance on the pipeline, this cost could be spread over decades, reducing the impact to the budget and downtime to operations. Through analyses to reduce the uncertainty in some parameters (inspection error, water hammer pressures, rate of deterioration as it becomes available) and using the fuzzy logic modeling to evaluate elements not well quantified, a logical prioritization and timing of replacement of the damaged pipe segments may be developed to keep risk to a minimum and efficiently replacing pipe when needed.

Conclusion

The large diameter transmission mains operated by the District must be extremely reliable since they carry most of the water for Fort Worth and surrounding communities. The cost for segment replacement is significant enough that only

segments that pose a risk of failure are to be replaced. The technology now available for inspection and analysis of strength allows the District to manage the repairs based on condition. The next step the District is taking will be to use predictive modeling of the loss of strength and couple that with risk analysis to further define future actions to be taken in maintaining the integrity of the pipeline in a cost effective manner.

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