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PIPELINE ASSET MANAGEMENT USING A GIS SOLUTION

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ABSTRACT

Effective asset management requires that utilities allocate scarce resources to high risk sections of their pipeline system while maintaining an acceptable level of risk throughout the system. This asset management approach requires the ability to evaluate criticality, extents of distress, and failure margin of each section of the pipeline system in order to identify pipes with unacceptable risk of failure.

A geographic information system (GIS) containing pipeline design and installation data, pressure scenarios, results of condition assessment, and embedded programs for structural evaluation and failure margin analysis contributes to an asset management program by aggregating pipeline data and allowing Utilities to make risk-based decisions. GIS-based tools allow Utilities to continually update the risk of failure of pipes in their system based on the latest condition assessment results and to select the most critical pipes for rehabilitation.

Tarrant Regional Water District (TRWD) utilizes a GIS database as a part of their asset management program. TRWD has performed electromagnetic inspection of their pipelines using remote field transformer coupling (RFTC) technology for the past fourteen years, and the GIS allows TRWD to update the risk of failure of distressed pipes based on the latest RFTC results. By continually re-analyzing each distressed pipe's risk of failure, TRWD has been able to repair the pipes at highest risk of failure.

This paper presents the GIS database and the programs written to perform structural evaluation and failure margin analysis within the database, and how TRWD has used the database in their asset management program.

INTRODUCTION

The goal of asset management is to maintain entire pipeline systems at an acceptable level of risk while minimizing overall costs. These systems often consist of many miles of pipeline with varying properties, installation conditions, and applied loads. Identifying individual pipelines or sections of pipelines at highest priority for advanced condition assessment, rehabilitation, and/or monitoring requires ranking sections of the system based on their criticality. Criticality can be determined based on the pipe risk of failure and constraints within the system (Zarghamee et al. 2012). This paper focuses on the use of available pipeline data and condition assessment results to calculate the risk of pipe failure and prioritize pipeline repairs.

Risk of pipe failure is defined as the product of likelihood of failure and consequence of failure. Likelihood of failure can be calculated in many different ways ranging from relative ranking of pipelines based on design, manufacturing, and installation data to failure margin analysis using risk curves and available distress data. Selection of a likelihood of failure calculation method depends on the available pipeline data, the available distress data, and the desired output, i.e., quantifying how close a pipe is to rupture or simply ranking the relative risk of distressed pipes. Consequences of pipeline failure must account for quantifiable damage, e.g., property damage and loss of service, and nonquantifiable damage, e.g., loss of life and loss of public trust. The consequences of failure and tolerable risk will vary among pipeline owners and even within a given system.

THE LAYERED GIS PIPELINE MODEL

Efficient and effective pipeline management necessitates having current and accessible data for each pipe in the system. Utilities possess an abundance of information concerning pipeline design, manufacture, construction, operation, and assessment. The GIS pipeline model must provide the detailed information necessary to make decisions regarding pipeline inspection, maintenance, and repair.

Maintaining and accessing the data can be a challenge as the numerous data sources may be dispersed throughout the Utility. Furthermore, the original construction plans often do not accurately reflect the existing current environment around the pipelines such as new land use or surface infrastructure information. Without consolidated environmental, condition assessment, and rehabilitation data, engineers may find it challenging to model, analyze, review or record changes to their pipeline infrastructure. As a result, many utilities are in the process of amalgamating their diverse data sets into a GIS.

In general, water network databases have represented pipelines on a global scale and have not incorporated details of individual pipe segments. Most often, the pipeline networks have consisted of nodes and edges where a node could represent a manhole or valve and the edge is the pipeline between the manhole and valve. Information about the edge pertains to the entire length of pipeline between the two nodes. This type of database structure lends itself to a number of network modeling options and a limited amount of asset management. For example,

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one can perform water traces, isolate valves, or determine disconnected areas of the network. Unfortunately, detailed information about individual pipe joints is not available using this type of data model. Alternatively, a well-structured database containing a layered model with pipe-specific information presents a wealth of information to pipeline operators.

A layered database model consists of a network level and a pipe-specific level. The network level uses a standard water distribution database where nodes and edges represent the broader pipeline without the detail of individual pipe segments. This level may hold information such as the type of pipeline, flow type, flow direction, etc. The network level has connections with network topology, coordinates, and other geographical data necessary for positional accuracy. Branching out from the network assets is information pertaining to distinct pipe segments as shown in Figure 1. In this level, the nodes are the ends of the pipe segment while the edge is the pipe invert. A pipe table lists each pipe segment and pipe-specific data such as wire pitch, wire size, mortar thickness, bell ring thickness, etc. This table links to other tables within the database which contain inspection, coordinate system, and topology data. In contrast to traditional water network modeling, a model with a layered data structure allows pipe sections to be tracked, analyzed, and modeled.

Pipe-specific data is necessary for managing distressed pipes. Many prestressed concrete cylinder pipe (PCCP) lines are inspected using electromagnetic technology, which reports the number and location of broken prestressing wires for each pipe inspected. Electromagnetic inspection results from multiple inspections on the same pipeline can be used to calculate a site-specific rate of wire breakage and to identify pipes with a high rate of wire breakage compared to the rest of the pipeline. This requires identifying individual broken wire zones on each pipe and tracking the number of wire breaks and location of each zone.

Designing a comprehensive database is the key to creating a successful GIS environment. The database structure should account for the following goals:

1. Develop an accurate system map that details each pipe section from bell to spigot, accurately reflects the current asset inventory and surrounding environment, and provides flexibility to adapt to changes in the pipeline and the surrounding environment.

2. Combine diverse sets of data from multiple sources in order to transfer all pipe section geometry, manufacturing, design, inspection, and rehabilitation information into a relational database that is GIS enabled.

3. Track history of distress magnitude and location.

4. Facilitate analysis and decision making by the user regarding pipe repairs, causes of distress, and risk of failure.

5. Support a decision-making process whose inputs may change over time as more information becomes available.

Pipe structural analysis, failure risk management, and cost analysis involve detailed information that can be provided with this new layered database model. Pipe-specific information can be transferred directly to programs that perform structural evaluation and failure margin analysis within the GIS.

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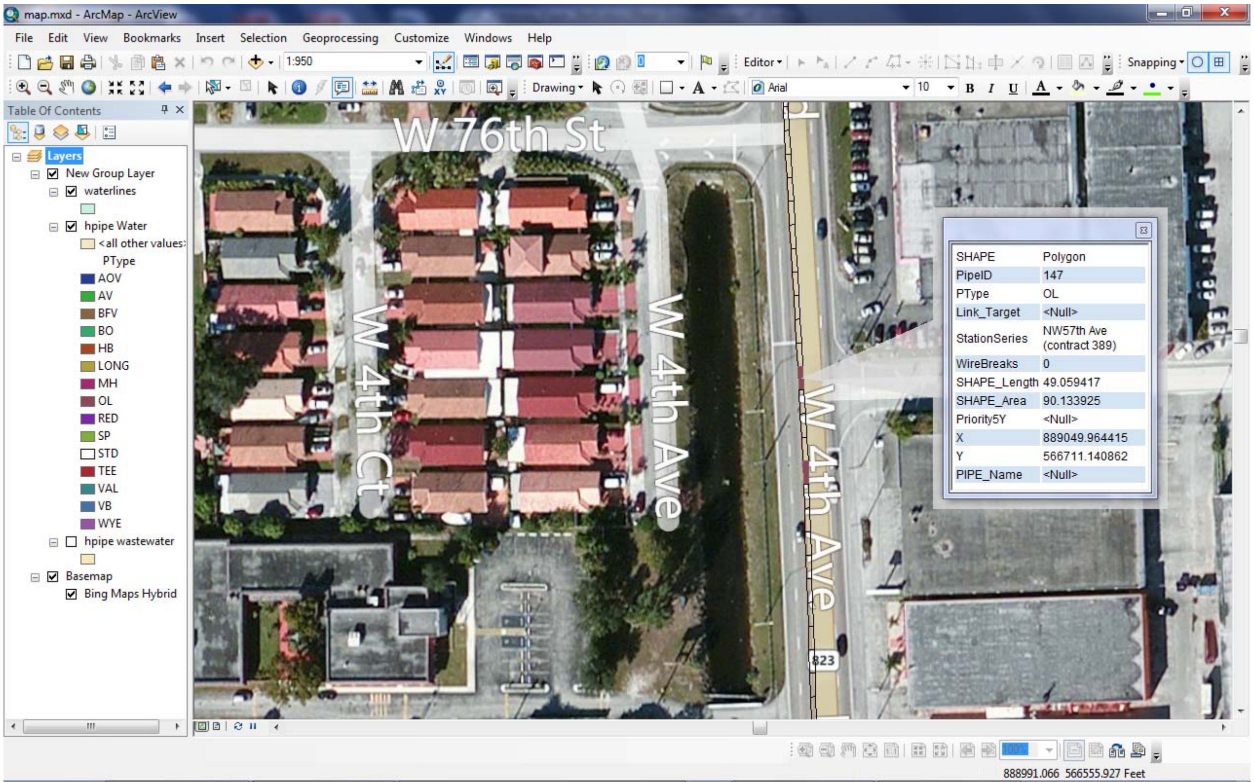

Figure 1 – GIS Graphical User Interface Showing Properties of Individual Pipe Segments

PROGRAMS FOR STRUCTURAL EVALUATION AND FAILURE MARGIN ANALYSIS

Simpson Gumpertz & Heger Inc. (SGH) and Pure Technologies (Pure) have developed a GIS-based tool capable of evaluating the structural adequacy of PCCP, calculating the risk of failure of distressed PCCP, and presenting the results within the GIS. The purpose of structural evaluation is to identify sections of pipeline that are more susceptible to damage and that are at a higher priority for additional analysis compared to other sections of the pipeline. The purpose of failure margin analysis is to quantify the risk of failure of distressed pipes and prioritize their repair. The programs are part of the GIS, and the results are presented in tabular form and through the graphical user interface.

Structural Evaluation Program

Structural evaluation is performed in accordance with limit states defined by AWWA C304 – Standard for Design of Prestressed Concrete Cylinder Pipe using the pipe properties and applied loads. Limit states curves, expressed in terms of applied earth load versus internal pressure, are developed using the computer program UDP and stored within the GIS database for each pipe class. The GIS user (User) identifies a pipeline station range and internal pressure scenario for which structural evaluation is desired, and the program evaluates each pipe within that station range based on its pipe class, soil cover height, and internal pressure stored within the database.

The structural evaluation results are presented in the form of ratios of the maximum applied pressure to the pressure that causes each limit state to be reached at the specified earth load.

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Ratios greater than 1.0 for a given limit state indicate that the limit state has been violated. The User may export the results and plot them as shown in Figure 2 using any commercial spreadsheet application, e.g., Microsoft Excel. Figure 2 shows the results for the maximum pressure envelope, coating cracking, wire elastic limit, and wire yield limit states as well as the soil cover height along the pipeline. In this example, the increased soil cover height near Sta. 159+00 results in violation of multiple limit states. The results of structural evaluation may be combined with the results of low-cost inspection technologies, e.g., pipe-to-soil potential measurements or soil resistivity surveys, to identify areas along the pipeline where use of advanced condition assessment technologies may be concentrated.

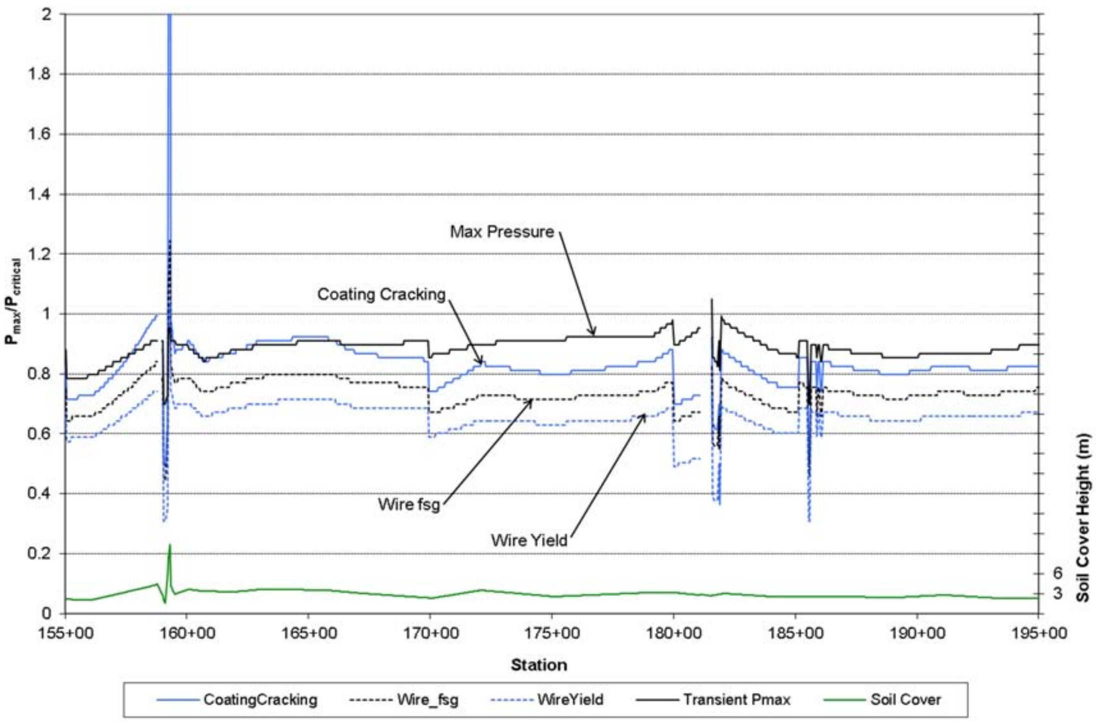

Figure 2 – Sample results of structural limit states evaluation along a pipeline

Failure Margin Analysis Program

Risk of failure of each distressed pipe is calculated based on the pipe design properties, the number of broken wires detected at the time of inspection, the effective number of broken wires at some time in the future (typically 3 to 5 yrs after inspection), the maximum pressures in the pipe, the applied earth load, and the consequence of failure of the pipe as indicated by the pipe importance factor. The results are summarized in the form of risk curves that show the maximum pressure in the pipe versus the effective number of broken wires for different limit states (i.e., serviceability, damage, and strength). Example risk curves are shown in Figure 3. The effective number of broken wires accounts for the estimated number and locations of broken wires, uncertainties in the estimated number of broken wires, and rate of progression of wire breaks. Each risk curve is developed for a specific pipe design and a specific cover height.

The risk curves are calculated based on an analysis procedure developed by SGH as a part of a study performed for the PCCP User Group and SGH internal research (Zarghamee et al. 2003). The basis of risk curves includes nonlinear finite-element analysis of prestressed concrete pipe

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with broken wires subjected to the combined effects of internal pressure and earth load, hydrostatic pressure testing of PCCP with induced and actual wire breaks, and field inspection of various PCCP with broken wires (Ojdrovic et al. 2011). The limit states curves divide the plots of pressure versus number of broken wires into repair priority zones, and each zone is assigned a priority, depending on the failure margin of the pipe and the need for repair.

Calculation of the effective number of broken wires accounts for the accuracy of the inspection technology and other uncertainties in the condition of wires and rate of wire breakage. The effective number of broken wires is equal to the number of broken wires as determined from inspection plus a certain number of wires that account for uncertainties due to inspection error, the degraded condition of wires adjacent to broken wires, and the increase in the number of broken wires over time. The effective number of broken wires is calculated internally by the program using an analysis that accounts for each of these uncertainties and the importance factor of each pipe. In calculating the effective number of broken wires, the rate of future wire breakage can be either obtained from historical distress data from other pipelines or calculated using the statistics of the annual increase in the number of broken wires based on subsequent inspection results as discussed by Zarghamee et al. (2011).

Risk curves are developed for each pipe class and a range of soil cover heights and are digitized for storage within the GIS database. Similar to the structural evaluation program, the User specifies a station range and pressure scenario for which failure risk analysis is desired. In addition, the User also specifies the number of years of wire breakage to include in the effective number of broken wires and whether the pipeline has cathodic protection. For each distressed pipe in the specified station range, the program selects the most recent inspection results stored in the database, calculates the effective number of broken wires, selects the maximum pressure based on the specified pressure scenario, selects the correct set of risk curves based on the pipe class and soil cover height stored in the database, and calculates the repair priority at the time of inspection and at the specified future time.

The results of failure risk analysis are presented as a repair priority and a repair priority index for each broken wire zone at the time of inspection and in future. The repair priority index is a decimal representation of the repair priority that indicates how close the distressed pipe is to each of the bounding limit states. The repair priority of a given pipe is dictated by the repair priority of the most critical broken wire zone on that pipe. Distressed pipes can be organized by repair priority index to prioritize pipe repairs.

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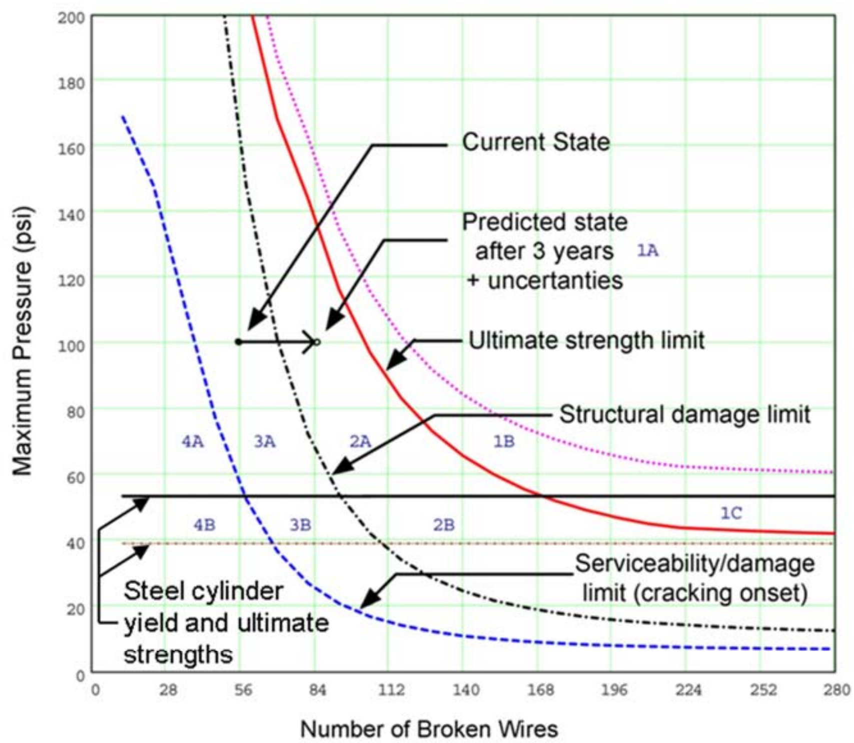

Figure 3 – Sample risk curves identifying limit states and repair priorities

TRWD APPLICATION

TRWD Background

TRWD owns and operates 164 miles of PCCP lines and provides water to more than 1.7 million people in the North Central Texas area. Pipelines in TRWD's system were installed in the 1970s and 1980s, and the frequency of failures began to increase in the late 1980s. TRWD embarked upon a program of periodic internal inspections of the pipeline and maintained a database of their observations, pipe repairs, and pipe failures. TRWD has since expanded their inspection program to a full asset management program consisting of periodic inspections using electromagnetic technology, on-demand calculation of failure risk based on the latest inspection results, and a GIS to process, store, and present the latest evaluation results for repair prioritization.

Data gathering and verification

Given the complex nature of pipeline deterioration, TRWD is utilizing a wide range of resources from various internal departments (Engineering, IT/GIS) and external consultants as well. To help manage the data, GIS staff at TRWD created a detailed geodatabase that included information on above ground features such as land use, soil conditions, utility networks, right-of-ways, parcel ownership, and aerial photography.

Beginning in the early 2000s, TRWD and Pure worked together to collect all of TRWD's diverse range of pipeline related data sets. TRWD handed over its array of lay sheets, spreadsheets and notes, which Pure organized into a logical data structure. TRWD's as-built drawings and lay sheets proved to be unreliable for providing accurate pipe details and positions of bends. Over time, TRWD and Pure inspected the entire system and used the results as a guide to create a GIS model by counting pipes and comparing to record drawings. Pure created tables for storage of pertinent pipe information. Each pipe segment was assigned a unique Pipe ID and given attributes based off of the lay sheets, including pressure class, station numbering, deflection information, type of material, size, length, cylinder thickness, etc.

After collecting the pipeline data, the pipeline location was determined using precise pipe positional data, pipe segment lay information, and GPS coordinates that TRWD had for a variety of surface features including air valves, blow offs, and manholes. Pipe segment lay information, taken from the RFTC inspection results, further uniquely identified each pipe segment between these surface features. Consequently, Pure was able to incorporate this information into a spatial database and provide TRWD with a set of geo-rectified drawings.

TRWD and Pure worked together to record infrastructure characteristics, defects, repairs and maintenance, giving TRWD's operators a visual representation and record of the pipeline's history. Information sets incorporated include: pipe defects, length, joints, position, class, soil resistivity or chloride concentration, surface infrastructure, topography, land use, customer locations, and operating pressure as well as results from RFTC inspections. TRWD has also added pipe-to-soil potentials, soil resistivity, replaced pipe segment history, test station readings, and anode information to our database. Completion of the pipe inventory was the most time-consuming phase of the data model implementation. The database currently includes tables and fields that contain a comprehensive view of TRWD's risk management data.

With every Pure inspection, six tables in the database are updated, reviewed, and added to TRWD's GIS model. Using these tables, TRWD is able to track damage for each individual segment and also compare trends in damage from one inspection to another. The damaged pipes, most of which are embrittled, are reevaluated annually to prioritize pipe replacement using the latest inspection data and an updated estimate of continued deterioration.

TRWD has inspected all 164 miles of PCCP, taking 10 yrs to do so, but as a result, TRWD now has an accurate map of the pipeline segments, appurtenances, and inspection results. All of this data is the foundation of many GIS analysis capabilities, so a complete and accurate database is crucial.

Incorporation of GIS into TRWD's asset management program

TRWD has pursued three paths to help mitigate failures on the transmission lines: transient pressure control, cathodic protection, and pipe segment replacement. First, the pump control valves were modified so a programmable logic controlled the valve closing times, reducing the transient wave dramatically. Secondly, cathodic protection was accomplished over a 5 yr period using zinc anodes attached to the pipelines developing a target instant-off potential of -0.85 volts (preferred range between -0.75 to -0.95). Lastly, TRWD prioritizes pipe replacements each year based on the results of failure risk analysis; this is where the GIS is instrumental.

Segment replacement was initially based on visual inspection. When the frequency of pipe failures began to increase in the late 1980s, the inspections were conducted in areas that were dewatered during the repair of a failure. If longitudinal cracks were found, the pipe was

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replaced. In 1998, TRWD employed PPIC (now Pure Technologies) to inspect the pipelines using their RFTC inspection technique. TRWD found that the technique, when calibrated, provided an accurate count of broken wire for pipes with shorting straps. With the creation of TRWD's geodatabase by PPIC, the results of these areas of distress could now be seen visually on a map and segments could be selected for replacement based off of known breaks and ranking. In 2001, TRWD joined with seven other agencies (the PCCP Users Group) to employ SGH to develop risk curves and better define pipe replacement based on wire breaks due to corrosion. TRWD continued this work with SGH to also evaluate pipes with wire breakage due to embrittlement. Embrittlement type wire failures differ from corrosion type in that the breaks are located randomly along the pipe length and around the pipe circumference. Since the breaks do not coalesce, the pipe maintains a portion of its prestress until the number of wire breaks reaches an upper limit, say 125 wires, at which point the pipe loses that prestress and is treated the same as if damaged with corrosion. TRWD used the risk curves to prioritize pipe repairs based on the results of RFTC outside of the GIS.

In 2006, TRWD assigned Pure and SGH with the task of creating a GIS tool that would integrate the inspection data and pipeline operation data that are currently in TRWD's GIS with the risk curves to evaluate the risk of pipe failure. The tool is based on the SGH's failure risk analysis and repair prioritization using the most recent RFTC inspection results and maximum pressures in the pipeline from different hydraulic working and transient conditions. The replacement program has now changed from one that replaces highly distressed segments to one that manages risk by replacing segments that are at the highest risk of failure using the SGH/Pure GIS tool.

The tool was designed to allow TRWD to customize pipeline evaluation. The options are given to choose which pressure scenario to evaluate (design class, maximum envelope pressure, etc.), evaluate with or without cathodic protection, specify a time to predict priority into future, analyze by one pipe or entire line, receive a priority or get a structural evaluation, and decide which pipes may have hydrogen embrittlement or not. SGH calculated the site-specific broken wire zone growth rate used to calculate the future number of effective broken wires based on the historical results of RFTC inspection. The output from the failure risk analysis program categorizes each distressed pipe into four repair priorities, with Repair Priority 1 being the most urgent category to be replaced immediately.

TRWD has continued its use of the RFTC technique, assaying a portion of the pipeline each winter. A total of 1,283 damaged pipe segments have been found, about 2.7% of the 47,666 segments in the system. There are currently 1,039 segments in the system with damage. To date, approximately 261 segments have been replaced or repaired. Following replacement of each damaged segment, TRWD cathodic protection staff perform forensic analysis to determine extents of wire break damage and their cause, comparing to original RFTC results. TRWD has expanded its asset management program to include on-demand calculation of failure risk using the risk curves with the latest RFTC inspection results and use of the GIS database to process, store, and present the latest evaluation results.

The current value of TRWD's pipeline infrastructure is approximately $900 million. The average pipe segment repair cost is about $40,000, carried out by TRWD's own staff. Replacing the 300 highest-priority segments would cost around $12 million spread out over a number of years, which is significantly less than the costs associated with replacing catastrophic failures. The GIS and GIS-based assessment tools assist in managing pipeline risk and life-cycle costs by prioritizing pipe replacements over the next 20 yrs to reduce the impact on operations budgets and downtime.

Selection of Pipes for Rehabilitation

TRWD uses a 3 yr horizon for the pipeline inspection and replacement process. The SGH/Pure GIS tool facilitates planning/budgeting by prioritizing which segments need to be replaced in the future. The list of repair priorities is combined with other factors, e.g., proximity to highly distressed pipes and pipe-specific rate of wire breakage, to select pipes for repair.

Every year, TRWD begins a new selection process to pick segments to be replaced the upcoming winter when demands are lower. TRWD reruns the SGH/Pure GIS tool incorporating the most recent inspection results. Since the wire failure mechanism of a damaged segment is often not known and the remaining strength varies widely between embrittlement and corrosion type wire failure, pipes are run under both scenarios (by changing the hydrogen embrittlement factor from 0 to 1). All damaged segments will then be put on a list that contain the priority rankings, hydrogen embrittlement factor, station numbering for location reference, etc. for further review.

All pipes in Repair Priority 1a are first priority, but the following factors are also taken into consideration when selecting replacement segments:

- **Consequences of failure.** Any pipes that are in urban areas, near major infrastructure, or have characteristics that increase the consequence of failure might be considered higher priority. Pipe with high consequence of failure can be assigned a higher importance factor, which will be incorporated into the failure margin analysis performed within the GIS.

- **Areas of previous damage.** All pipe replacement and failures are documented in GIS with a reason for replacement. TRWD has good documentation of areas known to have corrosion damage vs. wire embrittlement.

- **Time since last RFTC inspection.** Uncertainty in the RFTC results is greater in areas where the inspection was performed before 2003. As a result, pipes in these areas might be ranked higher. The district is currently trying to re-inspect some of these areas to bring more confidence in the inspection data and see any increase in wire breaks. The rate of change in wire breaks from one inspection to the next, no matter what year, is also a factor.

- **Corrosion and Corrosivity Data.** A check of pipe-to-soil resistivity or other corrosion/corrosivity measurements may be done of the areas with damage to compare with wire breaks. High pipe-to-soil potentials can be a cause of embrittlement and low potentials can leave pipes exposed for corrosion to occur. Although high voltage potentials with zinc galvanic anodes is highly unlikely, in decades past TRWD had an impressed current system in a particular area of the pipeline that led to embrittlement of wire due to excess potentials. A future goal is to use GIS to help TRWD with this analysis and compare with the damaged segments.

- **Proximity to high priority pipes.** Pipes that were not ranked a Repair Priority 1 may be selected based on their proximity to a Repair Priority 1 pipe. Replacing damaged

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segments that are adjacent save the district time and money by doing both at the same time and utilizing the equipment already there, rather than waiting until the less damaged segment moves up in the priority list. This is not always the case, but may be a factor in why a pipe was selected. Using the GIS, distressed pipes near Repair Priority 1 pipes can be easily identified.

- **Wire break concentrations near pipe segment ends.** There is significant uncertainty in the wire break predictions at the ends of pipe segments. TRWD is aware of this uncertainty due to past experience with occasionally finding more wire breaks than expected near the ends.

- **High pipe-specific rate of wire breakage.** Results of multiple RFTC inspections on a given pipe can be used to calculate the pipe-specific rate of wire breakage. A pipe with a wire breakage rate significantly higher than the average rate may be replaced due to the uncertainty in future broken wire zone growth.

TRWD has incorporated or plans to incorporate all of the above factors into the GIS to help in the pipe replacement selection process and to help mitigate pipe failures. TRWD's efforts have already proved valuable; in January 2013, several segments were replaced that had visible damage on the outer coating. As seen in Figure 4, a crack was found along one of the segments and as the mortar was chipped away a significant number of embrittled wires were found. TRWD's next step is to explore the use of GIS tools to perform spatial risk analysis and quantify threats and consequences of failure along the pipeline using the information contained in the GIS.

Figure 4 – Pipe selected for replacement Jan 2013

CONCLUSIONS

- The greatest advantage to the GIS approach is the ability to prioritize urgent pipeline repair needs in order to manage risk by replacing segments that are the highest risk of failure. This results in improved pipeline and associated asset management through

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more effective maintenance activities and the ability to achieve a more comprehensive view of the pipeline system in the capital improvement planning process.

- Repairs of distressed PCCP can be prioritized using a GIS-based program capable of calculating the failure margin of PCCP. The program can quantify the margin of failure of distressed pipes and prioritize repairs based on the latest pipeline inspection results.

- Structurally deficient sections of pipeline can be identified using a GIS-based program capable of evaluating the structural adequacy of PCCP based on individual pipe properties and the applied internal and external loads. The use of advanced condition assessment technologies can be focused on these sections of pipeline that may be more susceptible to damage compared to other sections of the pipeline.

- A robust asset management program that combines regular inspections, forensic analysis, and failure risk analysis on a pipeline gives an operator an understanding of past events, current events, and what events are likely to happen in the future. With such an asset management program in place, the lifespan of water transmission mains can be greatly increased, risk exposure reduced, and expenditures focused in areas of greatest benefit.

- TRWD has successfully used the SGH/Pure GIS tool to evaluate the risk of pipe failure and prioritize pipe repairs. TRWD's asset management program has concentrated repairs on the pipes at highest risk of failure and has spread pipeline maintenance costs over a number of years to ease funding issues.

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