RECENT ADVANCES IN PIPE WALL ASSESSMENT TECHNOLOGY

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ABSTRACT

Most of North America's oldest water mains are constructed of ferrous material, in particular cast iron, ductile iron, and steel. As utilities rarely have funds to replace all of these pipelines at the end of their design life, they are forced to carefully target their replacement and rehabilitation budgets. Critical for this targeting of funds is the availability of accurate knowledge of the actual pipeline conditions, in particular assessing the condition of the pipe wall and its impact on the remaining useful life of the pipeline. With this clear and impending need, a variety of technologies are becoming available for pipe wall assessment.

This paper details developments and advances over the past two years in several technologies for pipe wall assessment. The results provided by each technology are outlined, as well as how these results can be used to assess progression along the failure paths of various types of pipelines. The tools are grouped in a systematic way, illustrating how they fit into three fundamental philosophies towards condition assessment. Examples of their application are provided for tools advanced beyond the R&D phase.

FAILURE MODES OF METALLIC MAINS

Pipes fail when some portion of the pipe is no longer strong enough to withstand the stress applied to it. This can happen when unexpected stress is placed on the pipe, or when the pipe loses enough strength to be overcome by the planned stress of normal operation. In most cases, it is a combination of the two: an unexpected stress, such as a water hammer, causes a failure at a point that has been weakened by one or more factors, such as cracking or corrosion. (Makar et al, 2001)

Different types of pipe have various mechanisms of failure, and hence different failure rates. Cast iron pipes are by far the most prone to failure. Cast iron pipes corrode, are brittle, are prone to cracking, and generally employ bell and spigot joints that can lose their sealing integrity. Many older North American cities contain cast iron pipe installed in the 1800's, when methods of construction were not uniform and formal quality control (inspection) and pipeline standards did not exist. For example, oakum, lead, and leadite were used as joint-sealing materials before rubber gasket joints were available, which has led to degradation, leakage, and failure. Today, these methods would be considered poor construction practices but were common years ago.

Ductile iron pipes have failure mechanisms similar to cast iron pipes, but are less brittle. Thus, they do progress along the path of degradation more slowly, and are less prone to cracking. These pipes are capable of supporting large leaks for longer periods of time without immediate danger of failing.

As with iron piping, welded steel pipes are prone to corrosion over time, yet they are less prone to cracking, and their joints do not lose integrity. Steel piping fails primarily through corrosion pitting, leading to leaks of gradually increasing size along the welds, where material differences encourage corrosion. Because steel is a particularly malleable metal, these leaks form and grow gradually, and do not often lead to sudden bursting of lines.

Some of these failure mechanisms operate over very long periods of time, meaning that older pipes experiencing these conditions are more likely to fail. However, there are other factors at work: material or installation defects may surface over a relatively short period of time, problematic regions of a pipeline may be replaced or rehabilitated, and third party damage can cause a previously healthy pipe to degrade quickly. The net result is that age cannot be solely relied on as an indicator of an at-risk pipe.

A FRAMEWORK FOR PIPE ASSESSMENT TOOLS

As the number of tools for assessing pipe condition increases, it is important to consider the particular situation and address which tools are most applicable. This section shall present a framework consisting of two simple charts, which illustrate the different purposes of pipe assessment programs, and which tools are appropriate for each.

The first consideration is a means of organizing various approaches according to the information that they provide. This can be done by placing them on a two-axis grid, with the vertical axis indicating increasing resolution, and the horizontal axis indicating increasing coverage of physical inspections. The vertical axis would range from a single estimate of an entire pipeline's average condition (at the bottom), right through to detection of even the tiniest individual defects at the top. The horizontal axis would range from acquiring just a few local data points for an entire pipeline (at the left), right through to full circumferential testing of the entire pipeline (at the right). An illustration of such a two-axis chart is shown in Figure 1.

Figure 1: Pipe assessment chart.

The chart area can be grouped into four quadrants, representing the four basic methodologies of metallic pipeline assessment.

The lower-left quadrant represents assessing the general condition of entire pipelines, based on a minimal amount of physical data. This is generally known as a desktop study, in which experienced engineers will use design and environmental records, along with historical break records, in order to assess the remaining life, repair priority, or criticality of various pipelines.

The upper-left quadrant represents taking high-resolution samples of a pipe's condition at a relatively small number of points, and using these results to extrapolate the condition of the remainder of the pipeline. Technologies used include:

- Coupons and ultrasonic point tests: it is common practice in North America to take several samples using these methods, and then extrapolate the rest of the pipeline's condition based on an experienced engineer's judgment.

- Pipe samples: common practice in the UK is to cut 1-meter sections from a pipe and measure the corrosion pits; these results are statistically extrapolated through a well established formula.

- Non-destructive sampling: detailed full-circumferential scans are made of one to two meter long sections of pipe using electromagnetic tools, such as Broadband Electromagnetics, Magnetic Flux Leakage, or Pulse Eddy Current. Overall pipe condition is extrapolated by either statistical methods or an engineer's judgment.

The lower-right quadrant represents directly measuring the overall condition of large portions of a

pipeline. At present, the only testing method available that falls into this category is acoustic pipe wall assessment. In this method, the average wall thickness over intervals of pipe is calculated by taking extremely accurate speed-of-sound measurements, and applying a known relationship between two values. It is available in several forms:

- Averaged from hydrant to hydrant: leak noise correlators and induced noise are used to calculate the average wall thickness between hydrants, or other existing or bespoke access points.
- Averaged over short sections: by placing a mobile hydrophone into the pipe (available via SmartBall® or Sahara®), average wall thickness can be calculated over very short intervals.

The upper-right quadrant represents full testing of the entire pipeline for individual defects. This includes techniques that detect only certain defects, as well as the “gold standard” techniques that measure pipe wall conditions in great detail. These techniques generally involve inline testing of a pipeline, with methods such as:

- CCTV inspection: standard CCTV inspection vehicles can be used on out-of- service pipes. For in-service pipes, Sahara Video™ is available.
- Electromagnetic inspection: detect regions of wall thickness loss along the full length of the pipeline. Both high-resolution systems and medium- resolution systems are available.
- Inline leak location: detection of leaks of all sizes, as well as pockets of trapped gas. Available from SmartBall, as well as the Sahara.

This chart is useful in a number of manners. First, it should be observed that the vertical axis represents the amount of information gathered for each unit area of the pipe wall tested, whereas the horizontal axis represents the total area of the pipe wall tested. The total amount of information collected in any given method can thus be represented by the area within a rectangle formed by drawing lines downward and leftward from any technique’s point on the chart. The cost of inspections per mile covered will generally tend to follow the same pattern, with costs per mile assessed generally rising as you move from the lower-left corner to the upper-right.

RECENT TECHNOLOGY ADVANCES

Significant advances have been made in the past two years in both the acoustic pipe wall assessment technology, and the inline electromagnetic technology. Several of these advances have been subject to field testing over this period as well, which will be detailed below.

Acoustic Pipe Wall Assessment

Acoustic pipe wall assessment takes advantage of a known relationship between the speed of sound and wall thickness within a given pipe. An acoustic wave is induced in the pipe, and propagates as a compression wave in the fluid, and a dilatational wave in the pipe (the water hammer mode). As the wave travels, *the pipe will breathe on a microscopic level, and therefore the pipe will go into stress.* The thicker (and therefore stiffer) the pipe wall is, the less the pipe wall will breathe, resulting in a faster speed of sound in the pipe. From an intuitive perspective, this is akin to trying to run on a trampoline versus solid ground; as the bounding layer becomes more flexible, the propagation velocity decreases. The equation relating the speed of sound in a pipe and the pipe’s wall thickness is shown in Equation 1.

Equation 1: Wave Velocity - Wall Thickness Model

$$v = v_o \cdot \sqrt{\frac{1}{1 + \left(\frac{D_i}{t_r}\right) \cdot \left(\frac{K_l}{E}\right)}}$$

V_0 = speed of sound in water

D_i = internal diameter of the pipe

t_r = remaining pipe wall thickness

K_l = bulk modulus of water

E = Young’s modulus of pipe material

With a known distance between two acoustic sensors, and a method of measuring the time it takes

sound to propagate between them, the average pipe wall thickness between the sensors can be calculated. This technique has been employed for several years using pairs of external sensors to calculate average wall thickness between hydrants or service connections on distribution network piping. Recent advancements now allow this technique to employ mobile in-pipe sensors, providing average wall thickness measurements over much shorter intervals. This is particularly valuable on large diameter pipes, where the separation of access points can be thousands of feet, and the high per-foot cost of repair or rehabilitation yields a need for higher-resolution data, allowing for targeted rehabilitation.

A key recent advancement allows for the application of the mobile-sensor pipe wall assessment: the development of acoustic pulsers. These devices are attached to the pipe, and generate acoustic pulses, where the duration, waveform, and time between pulses are all carefully controlled. These pulsers are critical in performing accurate propagation time measurements. They can be attached to a main in a number of manners, as illustrated in Figure 2, and can be spaced at intervals of ~1,000 ft.

Figure 2: Acoustic pulsers attached to mains in a variety of manners.

Two deployment methods are available for the mobile-sensor version of acoustic pipe wall assessment: tethered, and free-swimming. Illustrated in Figure 3, the free-swimming version of the technology, a negatively buoyant ball rolls along the pipeline, propelled by the flow of water. The ball contains a sensor core housing both an accelerometer, for calculating position based on rotations, and a hydrophone to receive the acoustic pulses. Timing of pulses can be adjusted, allowing for different levels of resolution. The latest field trials, conducted in the Central USA, have demonstrated that a sufficient high resolution is available to detect pipe joints, whose thicker material has a notably higher stiffness. This allows results to be presented as average thickness per pipe segment, as illustrated in Figure 4.

Figure 3: Illustration of the free-swimming arrangement of acoustic PWA.

07	2	20	20	21	21	21	21	21	21	21	2
8	9	0	1	2	3	4	5	16			
4230ft							4330ft				

Lowered Stiffness
Figure 4: Sample Free-Swimming Pipe Wall Assessment Data

The tethered arrangement, as illustrated in Figure 5, offers the potential for even higher resolution and accuracy. In this arrangement, two hydrophones are attached to an umbilical cable, separated by a known distance. A pulser is used to generate acoustic waveforms, which are detected by both sensors. An odometer is also used to measure the length of cable deployed, providing absolute position of each measurement. Speed of sound calculations can be made in two different manners: by comparing the arrival times of successive pulses at the same sensor (as with the free-swimming version), or by comparing the arrival times of the same pulse at the two different sensors. The second method has a distinct advantage, in that the separation of the sensors is fixed, allowing it to be accurately measured and controlled.

Figure 5: Tethered arrangement of acoustic pipe wall assessment.

Field trials of the dual hydrophone tethered arrangement are currently underway. An example of raw data from a dual hydrophone inspection can be seen in Figure 6. This higher resolution method of collected wall thickness data is able to depict pipe joints.

Figure 6: Example of dual hydrophone PWA data.

Inline Electromagnetic Testing

Inline electromagnetic testing of metallic mains has been commercially available for several

decades, based on the Remote Field Testing (RFT) techniques. The efficacy of this technique is well-established; however the high cost and stringent pipe access requirements have resulted in limited use. This is particularly true for large diameter pipelines, where the requirement for a near full-diameter entry point is often not feasible.

There have been recent major advancement in this technology, addressing the issues of cost and accessibility. RFT technology has been mounted on an existing free-swimming multi-sensor pipeline inspection tool, allowing wall thickness testing to be conducted on metallic mains while they remain in service. Unlike conventional pipeline inspection pigs, this device takes up just a small fraction of the pipeline's diameter, with flexible fins extending out towards the pipe wall in all directions. This allows the device to be inserted into in-service transmission mains through openings as small as 12-inches in diameter. A robotic arm can be used to catch the device at the downstream end of an inspection run. Inspection of over 10 miles can be conducted with just a single launch and retrieval, with several options for launch and retrieval available, as outlined in Figure 7.

Figure 7: PipeDiver™ inspection platform for large diameter water pipelines.

Originally designed for in-service inspection of prestressed concrete cylinder pipe (PCCP), modification of this inspection tool for wall thickness testing of metallic mains has proven to be relatively straightforward. Both systems rely on a single signal transmitter, known as an *exciter*, to create an electromagnetic signal inside the pipeline. A second device, known as a *detector*, receives the electromagnetic signal, and changes in the signal are then analyzed to obtain information about the pipe wall conditions. In the PCCP assessment configuration (known as RFTC), a single detector is used in the center of the device, which allows for detection of broken prestressing wires that provide the structural strength of the pipe. This *center detector* is also sensitive to gross metal loss in metallic mains, and has been used for this purpose in the past, however this method only allows for identification of very large defects. The major advancement lies in the addition of several *petal detectors*, mounted on the fins of the tool, as shown in Figure 8, for increased sensitivity.

Figure 8: Modification of free-swimming tool to include petal detectors for wall thickness testing.

The electromagnetic field travels along two distinct routes between the exciter and detectors. The first route, known as the direct path, runs through the inside of the pipe. This field diminishes quite quickly, and fades significantly after roughly two pipe diameters. The second route, known as the remote field, travels through the pipe wall, along the outside of the pipe, and then back through the pipe wall again. This remote field signal carries with it information regarding the pipe wall at the point where it travels through the wall. With a separation of between two and three pipe diameters between the exciter and detector, the remote field signal is stronger than the direct field signal, allowing for favorable signal-to-noise ratios. As illustrated in Figure 9, the free-swimming tool configuration allows for optimal placement of the exciter and detectors, keeping them two to three pipe diameters apart.

Figure 9: Illustration of the remote field path, as used by the free-swimming pipe wall assessment tool.

Initial laboratory testing of the petal detector concept has indicated good sensitivity to moderate levels of corrosion. A test pipe was selected with a single corrosion pit, roughly 2-inches by 2-inches in size, at a depth of 50% of the pipe wall. Figure 10 shows the defect and the response obtained from a forward and reverse scan, proving the effectiveness of the petal detectors.

Figure 10: The expected response to the defect was clearly seen in the signal, establishing that a single petal detector can identify a 2" by 2" corrosion defect.

As the laboratory trials have successfully proven the concept of the petal detectors, a new six-detector device has been fabricated for field trial use. The six-detector system was fitted onto a manned cart for a pilot test inside a 60" dewatered steel pipeline. Figure 11 shows that the electro-magnetic data collected was able to clearly detect the spiral welds along the pipeline.

Figure 11: Six-detector electro-magnetic data showing spiral weld.

CONCLUSION

Most of North America's oldest water mains are constructed of ferrous material, in particular cast iron, ductile iron, and steel. Various types of ferrous mains (i.e. cast iron, ductile iron, and steel) have different types of failure mechanisms (e.g. cracks, pitting, corrosion, etc.), which can lead to different failure rates. It is important to consider these factors along with others, such as internal loads and leaks, when assessing the condition of ferrous mains.

Given the need for condition assessment, there have been recent advances in pipe wall assessment technologies, which include free-swimming and tethered techniques, as well as in-line electromagnetic testing. These technologies can be compared with older technologies in a chart of resolution versus pipe wall coverage. The technology capabilities allow each tool to be grouped into quadrants along the chart for comparison. A comparison of different tools and consideration of failure modes are all important when determining an applicable condition assessment program.

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