PILOT STUDY USING FIBRE OPTICS AND CORROSION SENSORS FOR CONDITION MONITORING OF WATER PIPES

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Abstract

The aging of water infrastructural pipelines and the needs to safely and economically extend the service life are the main drivers for real time monitoring of structural deterioration of water pipelines. Fiber optics sensors provide a means of detecting and monitoring pipeline defects in real time. A common application of fiber optics sensors is to measure the strain and temperature of pipelines by attaching the fiber sensors along the pipelines. Any abnormal change in temperature could be an indication of leak while any excessive change of strain is an indication of tampering or structural damage. This paper presents a pilot study which was aimed to investigate the fibre optics sensors and corrosion sensor as in-situ sensors to provide real time data on corrosion condition of pipelines. Such data would improve the targeting of inspection programs, and allow improved monitoring and decision making for pipe repair or replacement. Furthermore, the data could be used for development of improved deterioration models and thus enhance knowledge of pipe deterioration.

Keywords: pipes, fibre optics, sensor and corrosion

1. Introduction

Water pipelines play a pivotal role in a nation's economy, prosperity, social well-being, quality of life and especially the public health. After many years of service, the ageing and deterioration of water pipelines reduces the structural strength and hydraulic capacity (due to increased pipe roughness) of pipes. The structural deterioration is of greater concern because it causes structural failures of pipes in the form of pipe leakage and pipe burst with catastrophic consequences such as social discomfort, traffic accident and local flooding (Li and Yang, 2012). Therefore, increasing pressure is placed on asset managers and water authorities to improve the effectiveness of managing their assets through adopting more efficient, sustainable and proactive asset management strategies.

Structural failures occur when the structural strength of a pipe is lower than the stress caused by static and/or dynamic loads. Structural failures often start with cracks or fractures as a warning (causing pipe leakage) as seen with ductile pipe while pipe burst or rupture may occur without warning as seen with some brittle pipe. The structural strength is reduced due to the loss of pipe wall material and/or growth of cracks. Cracks often start as a defect in manufacturing, installation and deterioration stage. Corrosion of pipe material is the major cause for the loss of pipe wall. Corrosion and/or crack growth will over time significantly diminish the structural strength of pipes leading to structural failures under normal design loads.

Current management approach uses snapshot inspection techniques such as CCTV to periodically inspect pipes for making maintenance and rehabilitation decisions. Pipes subjected to inspection are often selected or prioritized based on risk management concept which considers historical failure, expert knowledge, failure prediction (by deterioration models) and failure consequences (Marlow et al., 2010). Though practically useful, existing deterioration models contain a high degree of uncertainty due to the lack of long-term observed data and the complexity of deterioration phenomenon, which involves different damage processes such as corrosion, mechanical stress and probabilistic damage due to overload truck and soil movement (Marlow et al., 2010). Furthermore, various pipe and environmental factors also affect the deterioration process of water pipes in a combined manner. As a result, the predictive information on current and future condition of pipes provided by deterioration models offer limited use in the risk-based management approach. While water industry continues to look for a better approach that can avoid the use of snapshot inspection techniques, increase accuracy in identifying pipes in poor condition and more importantly, provide real-time monitoring of pipeline conditions, the solution could be on the use of in-situ sensor technology. This paper presents a pilot study which examined the applicability of in-situ sensors using fibre optics and in-line corrosion sensors for real-time condition monitoring of pipes in meeting Industry's demand.

2. Background

2.1 Corrosion

Electrochemical corrosion is responsible for various types of deterioration that are commonly found in the water pipelines. For examples, corrosive soil was found to cause about 60% of corrosion induced failures of water pipes in US (Romer and Bell, 2004). In the same investigation, stray current accounted for 4%-7%, galvanic corrosion accounted for 7% and coating damage accounted for 12%. In other industries, Bardal (2003) summarized that general corrosion (31%) and pitting corrosion (16%) are commonly found in chemical industry. In an oil refinery in Japan, stress corrosion cracking and corrosion fatigue accounted for 40% of pipe failures (Bardal, 2003).

Metallic corrosion is considered as an electrochemical process which requires the form of a corrosion cell. The corrosion cell consists of 2 electrodes (called anode and cathode), an electrically conducting path (allowing movement of electrons between electrodes as an electric current) and an electrolytic solution (allowing the movement of ions). The electrochemical process of pipe corrosion occurs in a manner that pipe becomes electrically conducting path, internal fluid or external soil moisture become electrolytic solution and local areas of pipe become anode and cathode.

In general, there are two modes of corrosion known as uniform and localized corrosions. In uniform corrosion, local areas of pipe are very small (almost invisible) and constantly change between anode and cathode to form corrosion cell and thus produce uniform corrosion over entire pipe surface. Typically observed uniform corrosion is caused by wet environments with dissolved oxygen including moist atmosphere, neutral solution (e.g. water), alkaline solution (e.g. seawater), and acid solution. However, the rate of uniform corrosion often decreases with time due to the forming of oxide film of metal which does not stop but slow down the corrosion process since it acts as a barrier between un-corroded metal and corrosive environments.

$$Fe \rightarrow Fe^{3+} + 3e \qquad (1)$$

$$H_2O + O_2 + 3e \rightarrow 3OH^- \qquad (2)$$

$$6H^+ + 3e \rightarrow 3H_2(gas) \qquad (3)$$

As shown in Equations 1 and 2 (Bardal, 2003), iron easily give up electron in wet condition to become positive iron while dissolved oxygen combines with water and electron to produce hydroxide ion. The positive iron then combines with negative hydroxide ion to produce insoluble ferrous hydroxide (or rust). It should be noted that although salt is present in seawater, it does not involve in the chemical reaction but to provide a good conductor of electricity. Equation 3 shows corrosion of iron in dilute acid such as hydrochloric and sulphuric and where dissolve oxygen is not involved. Rust is a considered as a barrier that does not stop the corrosion process of iron but to slow down the corrosion process. Measures such as cathode protection and protective coating are very effective in preventing the uniform corrosion of iron.

Localized corrosion, on the other hand, occurs at a specific area on pipe surface where corrosion cell can be formed. There are many types of localized corrosion such as pitting corrosion, stray corrosion, galvanic corrosion and stress corrosion cracking. More details can be referred in corrosion textbooks. Localized corrosion is the combination of corrosion cells and other mechanisms and/or factors such as aeration cells and stress-assisted corrosion. Therefore, localized corrosions are more complex with many influential factors and consequently, are more difficult to be detected and protected than uniform corrosion.

2.2 Crack

Crack-like defects in pipe systems often develop during fabrication, installation or in-service operation. In fabrication, micro-crack is formed due to the inhomogeneity of material or manufacturing errors such as residual stress. In the installation stage, the micro-crack might grow under construction load or new crack is formed due to excessive construction load and direct impacts. In operation stage, existing cracks continue to grow or new crack is formed due to operational loads and corrosion. Pipe cracks are classified into circumferential and longitudinal cracks, internal and external cracks, and part-through and wall-through cracks. Some attributes of cracks such as shape (mostly elliptical), depth and length are found to affect the impacts of cracks on pipe integrity.

Two major concerns with cracks are crack propagation and crack opening area. If the crack propagation through the pipeline proceeds in an unstable manner, crack speed may reach up to 1500 m/s, and the crack can propagate for several kilometers until its arrest takes place (Murtagian et al., 2005). If there is an axial part-through crack in a pipeline wall and the crack driving force is greater than the material toughness, the crack will grow and eventually break cross the pipe wall producing a through-the wall crack. If the through-the-wall crack driving force is greater than the material toughness, the crack will propagate axially through the pipeline. If this situation does not occur, the through-the-wall crack will conserve the same dimensions without additional axial crack propagation, producing leakage of the contained fluid.

2.3 In-situ sensor technology

The use of sensor technology for real-time monitoring of infrastructure assets is increasing due to the recent improvement of sensor capability and the reduced cost of sensors (Sinha, 2003). Murigendrappa et al. (2004) used vibration-based technique to detect multiple cracks in long pipes containing fluid at different pressures For pipelines, Tennyson et al. (2005) showed that fiber optic sensors can be used to detect the wall strain of an existing water pipe in a pilot study in Alberta province of Canada. Jomdecha et al. (2007) demonstrated that acoustic emission sensors can be used in a real-time manner to detect and locate corrosion activity of pitting, crevice, uniform or stress corrosions. Li et al. (2007) demonstrated that electrical resistance sensor technique can be used to monitor the corrosion rate of steel pipes. For bridges, a range of electrochemical sensor techniques including linear polarization, electrochemical impedance spectroscopy and electrochemical noise has been used to study the corrosion of reinforce steel of concrete structures (Zhao et al., 2007). Despite this increase in the use of in-situ sensors, according to Marsh and Frangopol (2007), some challenging issues of using in-situ sensors remain, including (1) how to evaluate the sensor system performance, (2) how to infer the corrosion condition of assets in between sensor locations and (3) how to determine the number of sensors and their locations that can provide adequate monitoring of pipe network.

3. Pilot study

3.1 Fibre Optics sensor

Fiber-optic sensors (FOS) are a non-invasive tool for monitoring pipeline defects in real time. They offer significant advantages vs. conventional sensors as they are nonelectrical and intrinsically safe (Tennyson et al., 2005). They are also insensitivie to electromagnetic interference and can be employed close to pumps, motors, and generators. FOS have low transmission losses and thus are ideal for long-distance sensing. With an integrated software interface, FOS can provide measured data and receive operating parameters from operators in real time. FOS systems can measure structural displacements, vibration, temperature and strains. There are two types of sensor systems on a different principle.

Point sensors include fibre Bragg gratings (FBG) and Fabry-Perôt (FB) sensors (Tennyson et al., 2005). The FBG sensors reflect light with a change in wavelength that is proportional to the strain experienced by the optical fiber at the grating location. FP sensors also respond to strain by producing a change in wavelength, measuring a change proportional to a change in gap length between opposing optical fibers. These sensors are used for measurements at discrete points.

Distributed sensors include Raman and Brillouin Scattering-based sensor systems (Zhang et al., 2008). Both operate by measuring a change in wavelength of light scattered across a narrow range of frequencies due to displacements within an optical fiber. Raman scattering primarily measures temperature distributions along an optical fiber at predefined gauge lengths that can vary from 1 m to several meters. Brillouin scattering can measure thermal as well as mechanical strains along fiber of comparable gauge length. These distributed sensing systems can interrogate a single fiber across distances as great as 25 kms.

This study investigated the use of FBG sensor for measuring the strain of pipes. Figure 1 shows the fibre optic sensor attached to the top of the pipe by using glue.

Figure 1: FBR fibre optics sensors used in the pilot study.

3.2 LPR sensor

Linear Polarization Resistance (LPR) monitoring is an electrochemical method of measuring corrosion (Bardal, 2003). LPR monitoring has seen wide industry use for nearly 50 years and allows instant measurement of corrosion rate of ferrous metals. The LPR is based on a proven concept that electrical conductivity of a fluid can be related to its corrosiveness. In an LPR device, a two or three electrode probe is inserted into the piping system, with the electrodes being electrically isolated from each other and the piping. A small potential in the range of 20mV (which does not affect the natural corrosion process), is applied between the electrodes and the resulting current is measured. The polarization resistance is the ratio of the applied potential and the resulting current level. The measured resistance is theoretically shown to be inversely related to the corrosion rate. If the electrodes are corroding at a high rate with the metal ions passing easily into solution, a small potential applied between the electrodes will produce a high current, and therefore a low polarization resistance. In this study, a Model 6112 LPR CORRATER® Probe as shown in Figure 2 was used to evaluate the applicability of corrosion sensor.

Figure 2: LPR sensor used in the pilot study.

3.3 Experimental Description

Ductile iron pipes with cement mortal lining and 6 inch diameter are used for the experiment. Figure 3 shows the configuration of the pipelines which are supported using wooden bracket in a 2 meter interval. A water tank and a frequency-controlled centrifugal pump were used to run clean water through the pipelines in a loop. Together with the pump, a butterfly valve was also used to control the flow rate and pressure.

Figure 3: Configuration of the experimental ductile iron pipes

An FBG sensor with 3 grating points fabricated at 150 mm interval was used to measure the strain. From the principle of FBG sensor, each grating point is considered as a sensing element which can be used to measure temperature, pressure and strain. However, this study used all three grating points to measure strain. Strain measurement using FBG sensor was carried out in which the pipelines are subjected to various loading conditions using a mechanical car jack. Intensity-wavelength parameters are used to detect the change under different loading conditions. The micro-strain of the pipe subjected to internal pressure and external loading is calculated using Equation 1 (Spillman and Udd, 2011):

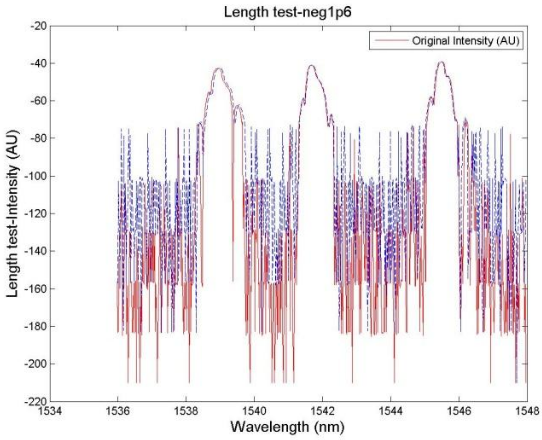
$$\text{MicroStrain} = 1000\times \text{WaveLenDiff (nm)} / 1.25 \qquad (1)$$

Internal corrosion rate of the pipe is measured using the LPR sensor mounted on the top of the pipes.

4. Results and Discussion

4.1 Detecting longitudinal upward loads (Length Test)

Upward point loads are introduced to the pipe at equal interval of 1.1 meters to see how FBG sensor can pick up the change of pipe strain. Since direct load measurement was not available, upward load was expressed by lifting the pipe to 10 mm at each position. The change in wavelength can be detected up to 5.9 meters away from the FBG sensor as shown in Figure 4a and 4b. Longer distances did not show any change. As can be clearly seen from Figure 4b, there are three peak values of intensity at three different wavelengths, which represent for 3 grating points. When the pipe was strained, there is a small shift or difference in wavelength of the 3 peak intensities, which indicate how strain is picked up by the FBG sensor. The wavelength difference is used in Equation 1 to produce strain magnitude. Figure 5 shows the micro-train along 7 positions.



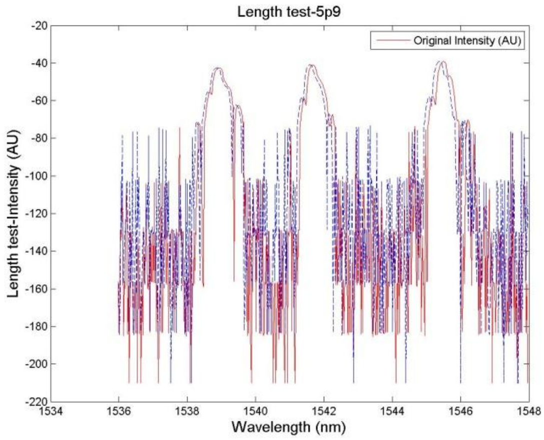


Figure 4a: Point load at 1.6 meter

Figure 4b: Point load at 5.9 meter

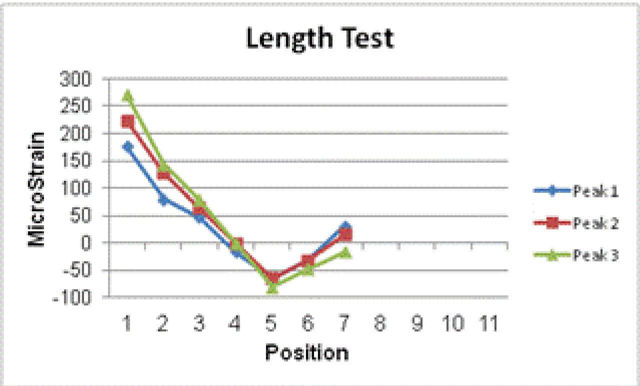


Figure 5: Microstrain versus loading position

Where referencing use author / date approach, such as the Harvard system or similar as in following example.

4.2 Detecting magnitude of point uploads (Increasing height Test)

Point load using car jack is applied at the pipe invert (i.e. beneath the sensor point). Since load measurement is not available, the upward movement of pipe is used as an indicator of the point load. 10 movements with 10mm each are upward applied to see any change in intensity-wavelength. Figure 6 shows such changes.

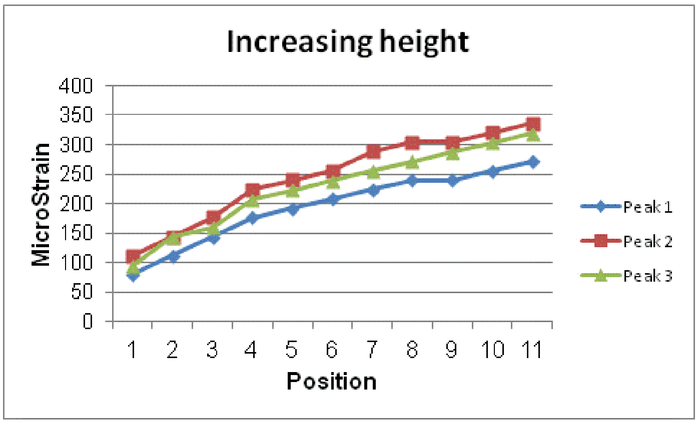


Figure 6: Microstrain versus increasing lifted heights

4.3 Corrosion rate

The pipeline was run at the internal gauge pressure of 100 kPa and the room temperature between 25-35^{o}C. The preliminary result in Figure 7 showed a tendency of increasing corrosion rate. However, the rate of increase is small over the first month. If corrosion rate of 100 micrometer per year (or 0.1 mm/year) is used in this one-month period, a typical steel pipe of 4 mm wall thickness would fail in 40 years due to corrosion. However, the corrosion rate became very high (up to 3.5 mm per year) after 4 months, which requires further investigation.

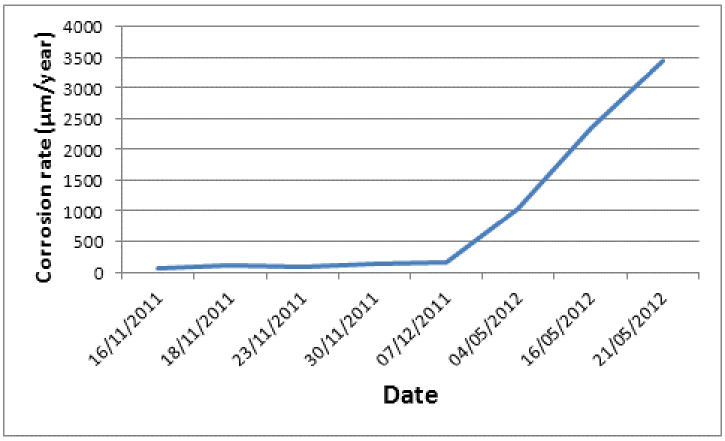


Figure 7: Internal Corrosion rate

4.4 Estimated Cost

Table 1 presents the acquired cost for fibre-optics and LPR sensors. As can be seen from Table 1, cost for fibre optics is quite low but the cost for the optical processor is quite high. On the hand, the cost for corrosion sensor including data logger is quite acceptable for practical implementation.

Table 1: Estimated cost for in-situ sensors

Cost ($AUD) / *Type*	*Sensor cost*	*Data-logger /Processor cost*	*Wireless communication*
Fibre optics sensor	*200*	*50,000*	*10,000*
LPR sensor	*1,000*	*2,000*	*10,000*

5. Conclusion

A pilot study for the application of fibre-optics sensor and corrosion sensor in real-time condition monitoring of water pipes was conducted. The results show that Fibre-optic sensor has the potential to be applied but the system cost might be too high for network wide application. On the hand, the LPR sensors showed a potential for network application in monitoring corrosion rate of internal and external surface of pipelines. Further investigation is required to provide detail analysis of the capability of fibre-optics sensors and corrosion sensor.

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