EVALUATION OF STRUCTURAL MONITORING METHODS FOR LARGE DIAMETER WATER TRANSMISSION PIPELINES

by

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ABSTRACT

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The water transmission lines span thousands of miles and form a significant part of the underground infrastructure of United States. The condition of water pipelines deteriorates with time and becomes more vulnerable to catastrophic failures and often results in costly replacement measures. With the advancement of technology, several new techniques have been developed for the condition assessment of water pipelines. However, no unified standards are followed for the selection of these technologies. Moreover, the current decision making methodology followed by water pipeline operators is usually based on individual experience and project requirements and resources.

This research presents a comprehensive overview of different structural health monitoring techniques available for continuous observation of the structural performance of large diameter water transmission pipelines. The capability of these techniques to monitor the structural health of a pipeline can be expressed in terms of a condition assessability index. Condition assessability index defines the technical feasibility of inspection technologies to monitor the failure indicators thereby assisting in preventing structural failure. This is accomplished by characterizing the pipe failure modes, mechanism and distress indicators for Steel Pipes (SP) and Prestressed Concrete Cylinder Pipes (PCCP), two main pipes used in large diameter water transmission projects. The condition assessability index, determined in this thesis, provided a basis for development of a decision support system which was used in the selection of a specific inspection and monitoring technique.

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LIST OF ABBREVIATIONS

ANST	American Society of Nondestructive Testing
AHP	Analytical Hierarchy Process
BOTDA	Brillouin Optical Time Domain Sensors
CCTV	Closed-Circuit Television
CI	Consistency Index
CR	Consistency Ratio
FBG	Fiber Bragg Grating
FPAV	Fire Plug Air Valves
GIS	Geographic Information System
GMM	Geometric Mean
GW	Guided Wave
IACC	Impressed Alternating Cycle Current
IPL	Integrated Pipeline
LED	Light Emitting Diode
MFC	Macro Fiber Composite
MISE	Magnetic Induction Sensors
MFL	Magnetic Flux Leakage
NDE	Non-Destructive Evaluation
NDT	Non-Destruc\ive Technologies
OTDR	Optical Time Domain Reflectometry
PCCP	Pre-stressed Concrete Cylinder Pipe

RI	Random Index
RFEC	Remote Field Eddy Current
SBS	Stimulated Brillouin Scattering
SCADA	Supervisory Control and Data Acquisition
SHM	Structural Health Monitoring
SP	Steel Pipe
TRWD	Tarrant Regional Water District
US	Ultrasonic
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION & BACKGROUND

This chapter presents a brief introduction to the history and classification of pipelines. It also discusses failure of pipelines and how this can be mitigated by effective use of pipeline monitoring methods.

1.1 Water Transmission Systems

The history of transporting water for human consumption started around 3500 years ago, when for the first time pipes were used on the island of Crete, Greece (James, 2006). With industrialization, the safe supply of potable water became one of the basic necessities of mankind. A massive amount of money is spent every year around the world on providing or upgrading drinking water facilities. The water supply infrastructure varies in complexity from simple, rural town gravity system, to a computerized, remote controlled, multisource system of a large city. However, the aim and objective of all water supply systems is to supply safe water for the least-cost (Swamee and Sharma, 2008).

Water transmission and distribution systems can be divided into four main components: (1) water sources and intake facilities, (2) treatment works and storage, (3) transmission mains, and (4) distribution network. The common sources for the untreated or raw water are surface water sources such as rivers, lakes, springs, natural and man-made lakes, and groundwater sources such as bores and wells. The intake structures and pumping stations are constructed to extract water from these sources. The degree of treatment depends on the raw water quality and the finished water quality requirements. A transmission system is designed to facilitate the transportation of large amount of water over great distances. The typical appurtenances of a transmission pipeline are inline stop valves, fire plug air valves (FPAV), drain valves, isolation valves and access points (Misiunas, 2005). If the flow of water in the transmission main is maintained by creating a pressure head by pumping, it is called a pumping main. Pipes with diameter more than 24 in. are generally considered as large diameter and is widely used for the purpose of water transmission. Steel Pipes (SP) and Pre-stressed Concrete Cylinder Pipes (PCCP) are typically used for large diameter transmission pipelines. Finally, a distribution network delivers water to consumers through service connections.

1.2 Present Condition of Water Transmission Systems in USA

The study, "Drinking Water Infrastructure Needs Survey and Assessment," published by the US Environmental Protection Agency (EPA, 2007) estimates the need for the next 20 years for construction and maintenance of water utilities to be $334.8 billion (2007-2026). Of this amount, 422 million is assigned to pipeline safety improvement which includes pipeline monitoring. This study emphasizes great concern in the structural health of large diameter transmission pipelines due the catastrophic nature of their failures. Therefore, it is necessary to gain a better understanding of the condition and performance of these water transmission pipelines. Effective implementation of pipeline monitoring techniques will provide operators with the knowledge that would enhance better identification of the risks they encounter. In addition this would also, facilitate the prioritization of the needs for investment and selection of the most appropriate remedial actions.

1.3 Structural Health Monitoring and Pipeline Inspection

Historically, the monitoring of pipelines involves many of the same ingredients as the structural health monitoring of structures such as bridges and buildings employed today. These ingredients include data collection and processing followed by analysis and decision making. The simplest form of structural monitoring is the visual observation and assessment of the structure. But the new technologies have developed more effective and sophisticated techniques for the continuous and real-time monitoring of the structural performance of infrastructure. Formal structural monitoring and interpretation using recording instruments began in the latter half of 20th century and gained momentum with the development of electronic data storage and computer data acquisition systems. Structural health monitoring is known by different names such as structural monitoring, structural integrity monitoring or simply monitoring. All of these terms essentially represent the same idea of acquiring, managing, integrating and interpreting the structural performance data at a minimum cost with minimizing the human interference in any of these steps (Brownjohn, 2007).

Pipeline monitoring techniques have developed significantly over the past decade. The most recent and popular of these developments are the real-time monitoring techniques. In this technique, a sensor or an array of sensors will be distributed along the length of the pipeline, or at recognized points of high loading. These sensors can measure strain and wall thinning due to the external loadings and internal pressure as well as the impact of environmental factors on the pipeline. Other applications of monitoring techniques include leakage detection and real-time detection of 3rd party intrusions.

There are two main methods to gather information about a pipeline. The first method is inspection which gives information regarding the existing conditions of the pipeline including all the past damages that the pipeline has been subjected to. The second method is monitoring that provides data regarding what is happening with the pipeline at a given time. It is evident that these two methods provide complementary information and provide a complete picture of the structural health of a pipeline.

1.4 Objectives and Scope

The main objective of this thesis is to identify the different techniques available to assess the structural health, leakage and third party intrusions for steel and PCCP water transmission pipelines and to calculate the condition assessability index[1] for each of these techniques. Other objectives of this thesis are:

1. Evaluate the different modes of failures in Steel and Pre-stressed Concrete Cylinder Pipes.
2. Prioritize the distress indicators for pipe failures based on the criticality of the physical, environmental and operational parameters.

Condition assessability index : The technical feasibility of inspection technologies to monitor the failure indicators thereby assisting in preventing structural failure [1]

3. Identify the critical areas in the Integrated Pipeline Project (IPL)[2] route and recommend suitable inspection and monitoring techniques.
4. Develop and validate a JAVA® based Decision Support System Software to help future users in choosing a suitable monitoring technique for their specific project conditions.

The scope of this thesis is limited to large diameter steel and PCCP pipelines (more than 24 in. in diameter) and for water transmission mains. This research focuses only on non-destructive evaluation (NDE) and Structural Health Monitoring (SHM) techniques; no destructive methods of pipe monitoring are included in this study.

1.5 Methodology

A thorough literature search was conducted to identify state-of-the-art technology that is available for the monitoring of pipelines. The sources used include government documents and published reports, books, journal articles, patents, conference papers, thesis and dissertations, and industry Websites. A survey was conducted to study the criticality pipe monitoring criteria and to prioritize the distress indicators. The most applicable technique for pipeline structural monitoring, leakage assessment and third party intrusions were selected based on this prioritization index. The formal steps for this study included identifying physical, environmental and operational indicators for selection of pipeline monitoring parameters and developing a condition assessability index based on Analytical Hierarchy Process (Saaty, 1994) to select the most applicable technique for the structural monitoring, leakage and third party intrusions. A JAVA® based decision support system was developed to facilitate the selection of a suitable pipeline inspection and monitoring technique. The detailed methodology is provided in Chapter 3.

1.6 Expected Outcome

The outcomes of this thesis include:

- An overview of techniques which can successfully be used for monitoring water transmission mains.

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[2] This project will be described later in this thesis.

- An evaluation of existing techniques available for monitoring the water transmission pipelines for effective management.
- A condition assessability index for pipeline monitoring technologies for the selection of a suitable technique for a large diameter water transmission pipeline.
- A JAVA®-based software tool to assist in the selection of the most suitable technique for the monitoring of large diameter pipelines.

1.7 Chapter Summary

Recent developments in the field of structural monitoring and techniques for water transmission pipelines provide new options for assessing the conditions of these pipelines. This study will be helpful in illustrating the applicability of different monitoring techniques for large diameter water transmission pipes.

CHAPTER 2

LITERATURE SEARCH

2.1 Introduction

This chapter consists of a review of findings from a comprehensive literature search that was conducted as part of this research. As discussed in Chapter 1, literature search was used as one of the means to understand existing research works on this topic and to gain a better knowledge of applicability of structural health monitoring techniques in large diameter (more than 24 in. diameter) water pipelines. The subjects searched include (i) failure mechanism of steel and PCCP pipe materials, (ii) monitoring techniques for both of these pipe materials, and (iii) capabilities and limitations of each of these monitoring techniques.

2.2 Pipeline Deterioration Mechanisms and Failures

Exposure of water mains to aggressive environmental conditions and harmful reactions can lead to significant deterioration of the reliability of delivering safe drinking water. *Figure 2.1* illustrates the so-called bath-tub curve describing the life cycle of a typical buried pipe. The first phase, also known as the burn-in phase describes the period after installation, the reason for this failure being human factors like faulty manufacturing of pipe or faulty installation at the site. During the second phase, i.e. the in-usage phase the pipe operates relatively trouble free, with a low failure frequency. The third phase, also called wear-out phase, sees an exponential increase in the frequency of failure due to the pipe deterioration and ageing (Rajani and Kleiner, 2010).

The deterioration of pipelines can be categorized as the following:

i. Structural deterioration, which reduces the structural resilience of the pipes, thereby reducing the capacity of the pipes to withstand various types of stresses imposed on them.

ii. Deterioration of the inner surface, resulting in diminishing the hydraulic capacity of the pipe, degradation of water quality and at the same time reducing the structural resilience of the pipe.

Of the two causes mentioned above, external corrosion is the principal contributor to structural failure of pipes (Reed et al., 2004).

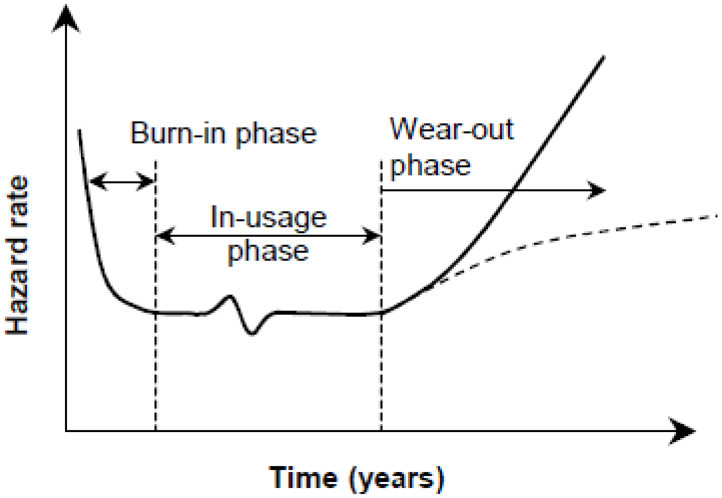


Figure 2.1 The Bathtub Curve of the Life Cycle of a Buried Pipeline
Source: (Rajani and Kleiner, 2010)

2.3 Steel Pipes (SP) and PCCP Materials

Steel pipe is a flexible pipe and when it is buried in soil, the pipe and soil work together as a system in resisting the load. Hence, there is a reduction in the load imposed on the steel pipe because of its flexibility, and this phenomenon is called arching. PCCP on the other hand is a rigid pipe, which receives negligible support from the surrounding soil and the pipe carries majority of the load imposed on it. Both these pipes have distinct differences in their failure mechanism.

Steel pipes used for water transmission mains are generally lined internally using cement mortar or polyurethane, and coated externally using tape, coal tar enamel, cement mortar, epoxy, or polyurethane. Contemporary steel pipes used in the water supply network have a diameter of 14 in. or larger. The characteristics of steel pipe are (Makar and Chagnon, 2010; Thomson and Wang, 2009):

- Thinner wall than grey cast iron or ductile iron pipes,
- High strength with ability to deflect without breaking,
- Shock resistance,
- Lighter weight than ductile iron pipe,
- Ease of fabrication of large pipe,
- Availability of special configurations by welding,
- Ease of field modification,
- Protective coating externally,
- Cathodic protection is routinely installed, and
- Generally lined pipe.

Main forms of failure observed in steel pipes are break failure, longitudinal cracking and pipe bursts. Break failure is caused by pipe wall weakening due to pitting corrosion. General and local corrosions and graphitization can cause thinning of pipe walls which leads to longitudinal cracking. Third party damage and damage from to nearby construction activity generally causes pipe bursts. When a pipe that is already weakened when is subjected to high external load the pipe fails due to buckling. The transient pressure or water hammer can cause bursts in such pipes. (Gostautas et al., 2006).

Pre-stressed Concrete Cylinder Pipe (PCCP) is the most common configuration of custom designed concrete pressure pipes produced in North America under AWWA standard C301(Mergelas and Kong, 2001). The characteristics of PCCP pipes are:

- Rigid pipe and hence depends on its pipe wall for carrying the external load,
- Rigid and durable in operation,
- Takes advantage of the compressive strength and corrosive resistant properties of concrete,
- Takes advantage of tensile strength properties of pre-stressing wire,

- Adding cathodic protection systems can lead to hydrogen embrittlement of pre-stressing wire and subsequent pipe rupture,
- Designed for the external load the pipe will be subjected to, and
- Pipe degradation in particularly aggressive soils, corrosion of pipe canister, concrete damage due to improper installation methods.

PCCP is mainly of two types, Embedded Cylinder Pipe and Lined Cylinder Pipe. Embedded cylinder pipes are PCCP pipes of diameter more than 48–in. The most common modes of failure of PCCP are wire breaks and delamination, both caused due to external corrosion.

When a significant number of the wires break in the same area of the pipe, the concrete no longer remains in compression causing the pipe to collapse. Furthermore, this could also lead to damage of the mortar coating around the pipe, which exposes the wires to further corrosion. Hence, the priority in PCCP pipe monitoring is to detect the corrosion activity and wire breaks, and detecting the damage in concrete on the inside of the pipe. It is observed that PCCP does not tend to leak as a precursor to failure, but fail catastrophically. When PCCP is exposed to high levels of chlorides, rapid corrosion of the steel wires occurs (Royer, 2005).

2.4 Non Destructive Evaluation Techniques

According to American Society of Nondestructive Testing (ASNT); “Non Destructive Evaluation is the examination of an object, material or system with technology that does not impair its future usefulness” (www.asnt.org). NDE technique is used to measure and analyze the quantitative characterization of materials, tissues and structures by non-invasive means. Ultrasonic, radiographic, thermographic, electromagnetic, and optical methods are generally used to investigate and characterize the subsurface features of a material. These techniques are widely used in non-invasive medical diagnosis, intelligent robotics, security screening, as well as flaw detection and structural health monitoring of civil structures.

The past decade has seen several non-destructive technologies (NDT) being developed to inspect water pipelines. Some of these technologies exploit the specific pipe material properties and hence they are not applicable to all pipe materials. The main advantages of using NDE techniques include extensive use in the water transmission industry and their wide acceptance. The measurement using these techniques can provide data about the structural integrity of structures such as wall thickness or crack detection. It can also measure the environmental conditions like soil resistivity and ground stability.

The disadvantage of NDE techniques is that the sensing mechanism used is typically only temporarily installed to the pipeline structure; hence the testing is only performed at scheduled intervals. Therefore, this method relies on a predetermined schedule for testing. For a damage which occurs on a long-time scale, such as corrosion, this schedule is usually sufficient to detect the damage before it poses a threat to the structural integrity of the pipeline. However, with short time scale events, such as excavation or an earthquake, the testing schedule may allow the pipeline to operate under dangerous conditions. Another limitation is that some of these techniques require the pipeline to be taken temporarily out of service. This aspect of the testing increases the potential cost of NDE techniques (Dingus et al., 2002).

2.5 Applicability of Pipeline Monitoring in Pipeline Failure Management

Pipeline failure management is one area that is gaining increased popularity in the underground pipeline industry. Since pipeline failure cannot be fully prevented, failure management is a part of the everyday management of the underground infrastructure. Depending on the timing of failure, two types of pipe failure management strategies can be defined: proactive failure management, when the pipe repair/replacement decisions are made prior to prevent the failure, and reactive failure management, when the repair/replacement is performed only after the failure has occurred. *Figure 2.2* presents a pipeline asset management cycle which illustrates the different steps in this process. Inspection and gathering data is a significant milestone and becomes a basis to the subsequent assessment options. NDE and real-time monitoring techniques are ideal candidates for this stage in asset management as they provide reliable data about the current state of the surface and subsurface condition of the pipe structure. This data can be fed into the condition assessment phase where the failure mechanism can be investigated and necessary steps can be taken in subsequent steps (Lillie et al. 2005).

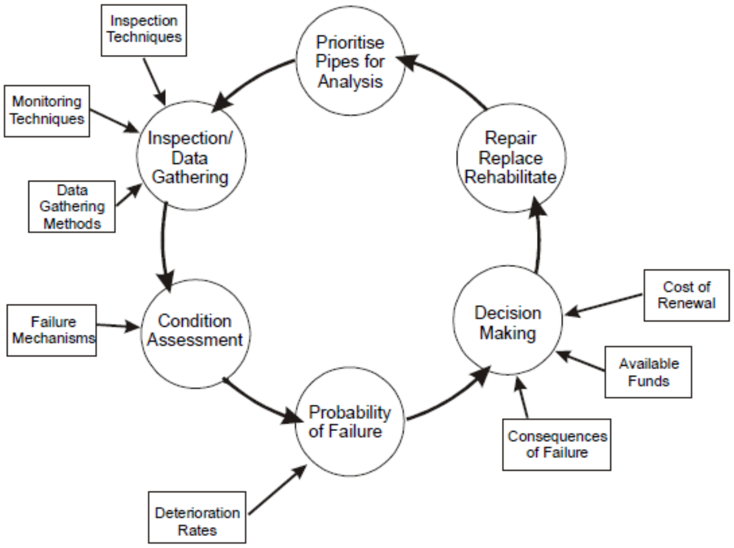


Figure 2.2 Pipeline Asset Management Cycle
Source: Makar and Kleiner, 2010

2.6 Structural Inspection and Monitoring Techniques for Steel Pipes

The different structural inspection and monitoring techniques for steel pipe are discussed in this section.

2.6.1 CCTV with Laser Profile Adapters

CCTV is one of the most common visual inspection techniques used in water pipelines. However, this technique only provides unprocessed data, and assessment of change in pipe shape and size is difficult and inaccurate. Profiling adapter is a special attachment that can be added to the front of the CCTV camera. These cameras are mounted on remote-controlled platforms and video recording is controlled remotely. The profiling adapter projects a ring line of laser beam onto the pipe section. Any distortion in the pipe wall will be made evident by this light ring. The CCTV image is digitized by an electronic frame grabber and the light ring image is located and distortion is calculated by the specially developed pattern-matching software (Duran, 2003).

Capabilities:

- Can measure with an overall accuracy of 0.2%,

- Can process 5-6 profiles per second, and
- Can be used in situations where accessibility is difficult and lighting is poor.

Limitations:

- Can be used only for circular pipes, and
- Data could be lost in areas with encrustation, holes, inlets, etc.

2.6.2 Electromagnetic Methods

The two major techniques based on electromagnetic principles are Magnetic Flux Leakage (MFL) and Eddy Currents. They are applicable to steel pipes and pipes that contain steel components.

2.6.2.1 Magnetic Flux Leakage (MFL)

This method works on the principle that when a magnet is placed next to a pipe wall, most of the magnetic flux lines would pass through the pipe wall. That is, pipe wall is a preferred path for the flux. This method can be used to measure leakages and the remaining metal loss of steel pipes. The MFL pigs are positioned on the inside of the pipe. These pigs consist of an array of powerful magnets which are will magnetically saturate the pipe wall in order to accurately measure the corrosion and metal loss. At the metal loss region, there will be a flux leakage, and the sensors will record higher flux density or magnetic field at that location. This indicates the presence of anomaly and to characterize the anomaly, the leakage field must be analyzed (Thomson and Wang, 2009).

Capabilities:

- Can detect and characterize metal loss from corrosion, one of the major reason for steel pipe failures, and
- High resolution and extra high resolution MFL tools can provide better detection capabilities.

Limitations:

- As currently used, MFL tools cannot detect all metal loss or reliably detect other defects such as axial cracking, and
- Does not provide continuous real time monitoring.

2.6.2.2 Remote Field Eddy Current (RFEC)

RFEC method is based on the principle that when an energized coil is brought near the surface of a metal component, eddy currents are induced in the system. The measurement of distortion in the preferred flow pattern of the eddy current indicate defect blocks and this change is measured and displayed in a manner that indicates type of flaw or material condition. A typical set up consists of an exciter coil that generates a direct electromagnetic field that travels inside the pipe. A small magnetic field sensor is positioned some distance away. Simultaneously, the exciter generates another indirect field that travels through the pipe wall with minor attenuation. Changes in field strength and attenuation are dependent on pipe wall thickness and thus the signature of these changes enables the determination of pipe wall thickness. The defects in the pipe wall thickness is indicated by the anomaly in the magnetic field produced by the combination of the direct and eddy current induced magnetic fields (Rajani and Kleiner, 2010; Reed et al., 2004).

Capabilities:

- The equipment can be introduced inside the pipe through fire hydrants or other access points along the pipe

Limitations:

- Most systems are frequency dependent or have a limited number of frequencies in their operating range. This limits the detectability of material thickness variations,
- The transmitter and receiver size and shape affect the operational frequency, so antenna configuration is not easily altered to suit survey configurations, and
- Does not provide continuous real-time monitoring.

2.6.3 Ultrasonic Technologies (US)

Ultrasonic measurements are among some of the best-established methods for simple external testing of points along a steel pipeline wall. Ultrasonic monitoring measures the propagation time for high frequency, short wavelength mechanical waves through metallic pipe wall, and this data is correlated with the pipe wall thickness. The equipment is generally in the form of hand-held instruments where a probe is positioned on the metal. The tool is calibrated to provide a direct thickness reading, which can then be compared with the original wall thickness (Reed et al., 2004).

Capabilities:

- The resolution of the equipment makes it possible to identify small areas of wall loss, and
- Ultrasonic tools are comparatively inexpensive, and hence it is a very commonly used and proven technique.

Limitations:

- Most ultrasonic devices require contact with clean metal, which involves removal of coatings, linings, and corrosion products, and
- These measurements are point readings of the depth, and there can be substantial variations that are not detected between the chosen points.

2.6.4 Fiber Optic Sensors

Optical fiber is a thin, flexible, transparent fiber that can be used widely for remote sensing. Fiber-optic sensors (also called optical fiber sensors) are fiber-based devices for sensing some quantity, typically temperature or mechanical strain, but sometimes also displacements, vibrations, pressure, acceleration, rotations, or concentrations of chemical species. They are usually made with two materials with different indices of refraction. Index of refraction is the ratio of speed of light in vacuum relative to the considered material.

The fiber itself consists of core, cladding with lower refractive index usually made of silica glass or plastic and a protective outer coating. The cladding is provided to guide the light along the core by using the principle of total internal reflection.

The general principle of fiber optic sensor is that light from a laser or any other super luminescent source is sent through an optical fiber and when these optical fiber experiences subtle changes in parameters there will be a change in the measurement of light reaching the detector. The components of a typical fiber optic system are

Transmitter: LED or Laser Diode

Receiver: Photodiode, which converts Optical Energy into Electrical Energy

Optic Fiber: They are broadly classified as Single-mode fibers and multi-mode fibers.

Single-mode Optical Fiber (also known as monomode optical fiber or unimode fiber) is an optical fiber designed to carry only a single ray of light (mode) and the light takes a single path to reach its destination. Single-mode fibers are most often used in high-precision scientific research because the allowance of only one propagation mode of the light makes the light easier to focus properly.

Multi-mode Optical Fiber is widely used for communication of data over short distance, such as within a building or on a campus. Multi-mode fiber has larger core size than single-mode fiber, which enables them to have more than one propagation mode. In this case the light is free to take many paths, which leads to spreading of the pulse called dispersion. *Figure 2.3* shows the sensor performance, environmental, and economic characteristics that needs to be considered when selecting a fiber optic sensor.

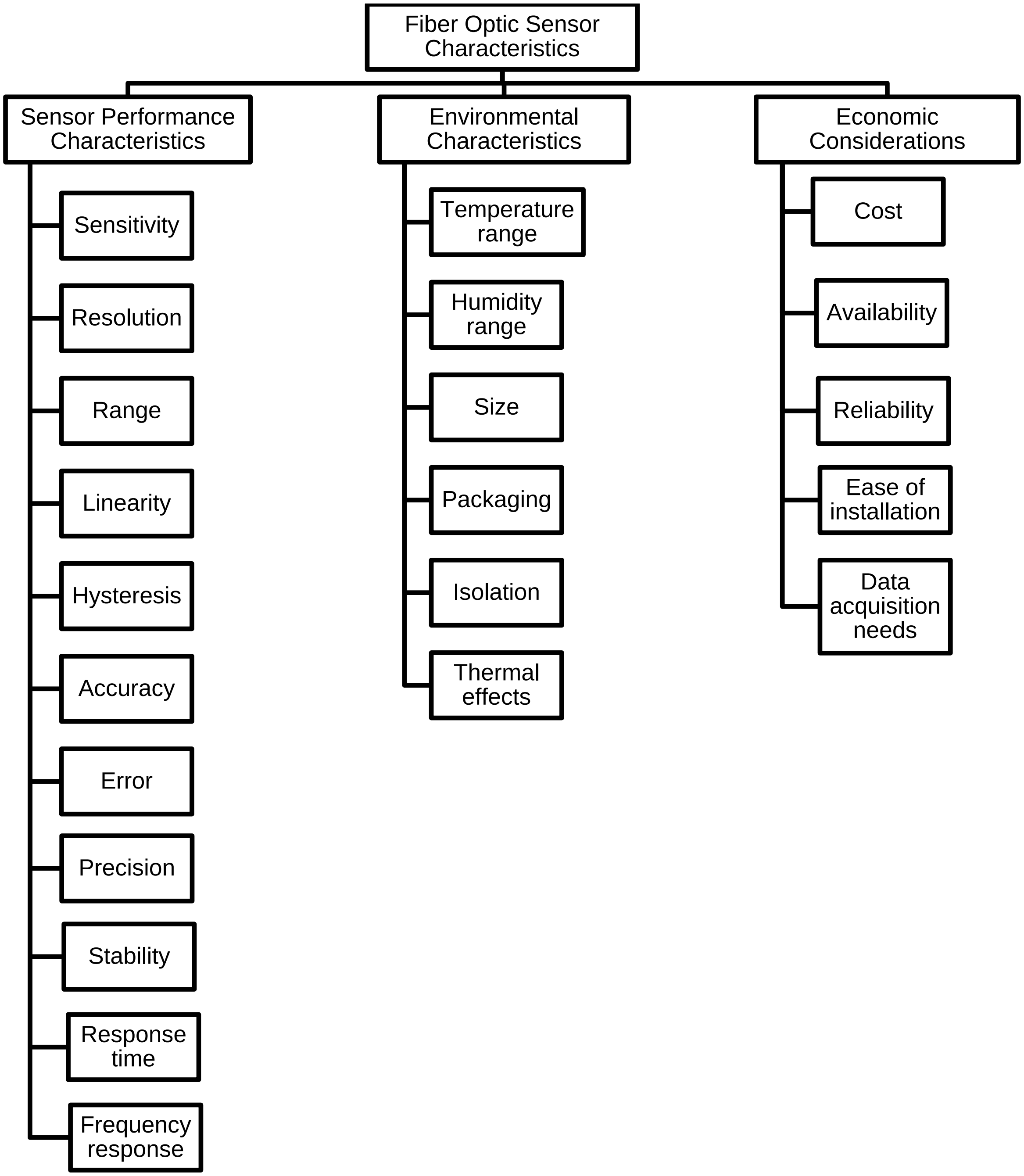


Figure 2.3 Fiber Optic Sensor Characteristics
Source: (Zou and Feng, 2008)

2.6.5 Fiber Bragg Grating (FBG) Sensors

Fiber Bragg Grating Sensor Arrays are encapsulated in a small diameter fiberglass cable of circular section inserted in an outer polymer tube. The outer polymer tube allows the inner cable to expand and contract freely with the temperature variations. The packaging protects the fiber and makes the sensor robust and easy to handle and install. Any strain or temperature on the sensor surface is linearly converted in a wavelength shift in the Bragg Grating and this can be very accurately measured using a range of Fiber Bragg Grating interrogators. The choice of materials allows a very good and fast response to thermal changes while the small size allows the sensor to be embedded in a number of materials. A temperature sensing cable is to be used along with a sensing cable for necessary temperature compensation. These sensors can be attached to structures using appropriate adhesives or can be welded on to the pipe. These sensors can measure data on a real-time basis and can use data acquisition systems at designated points to access the data on a regular basis. *Figure 2.4* describes the principle of FBG sensors (Tennyson et al., 2005).

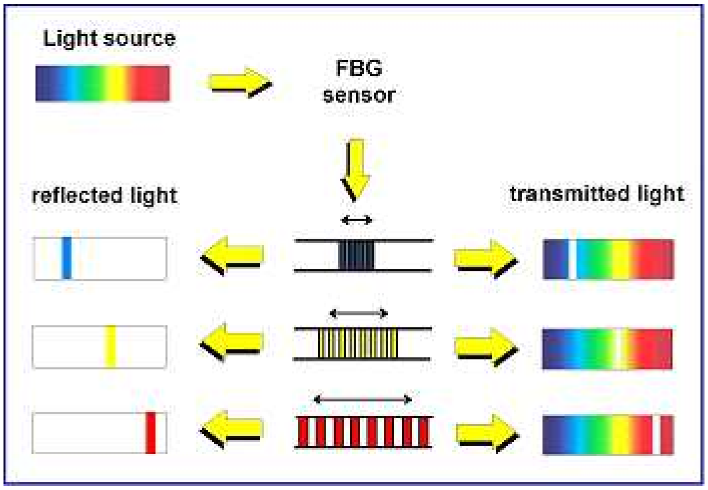


Figure 2.4 Fiber Bragg Grating Sensors
Source: www.fos-ta.com

2.6.6 Brillouin Optical Time Domain Analysis (BOTDA) based Sensors

Brillouin scattering is a type of reflection that occurs when light is shone into an optical fiber. An optical fiber guides not just light waves, but also naturally occurring sound waves. An interaction between the light waves and sound waves traveling within the fiber causes Brillouin reflections. Brillouin reflections are very sensitive to changes in the fiber arising from external effects such as temperature, strain and pressure.

Fiber optic sensors based on Brillouin scattering can be used for real-time monitoring of long distance pipelines. This can measure the strain and temperature over long distances at customized spatial resolution. Strain monitoring systems detect ground movement, whereas temperature measurements inform as to soil property change. The data is measured continuously on real-time basis and this helps the data acquisition system measuring strain can be placed at designated locations. The data can be analyzed using the automated software which would analyze the incoming signals and would provide warning signals when the strain is above a designated limit.

In BOTDA-based technique, the sensing medium is a standard single-mode optical fiber. The sensing mechanism is based on the Stimulated Brillouin scattering (SBS) effect in which a counter-propagating light wave (probe) is amplified at the expense of a pump light wave. The interaction between the pump and probe reaches the maximum when the frequency difference between the two light waves equals the acoustic mode frequency of the fiber, known as the Brillouin frequency n_B. Typically, the Brillouin frequency is about 10.85 GHz. The Brillouin frequency is proportional to strain and temperature variation. Thus, this approach is a method of choice for sensing of mechanical and thermal effects (Zou and Feng, 2008).

Capabilities:

- Immunity against electro-magnetic fields, high voltage, lightning, explosive and chemically aggressive or corrosive media, high and low temperatures, and

  Light-weight, flexibility, low thermal conductivity, low loss of signals, and long range signal transmission.

Limitations:

- Relatively new technique and so history of successful installation in case of water mains are limited, and
- Expensive and requires sophisticated data acquisition and data processing units.

2.6.7 Guided Wave Technology (GW) with Smart Materials

Recently the use of Lamb wave technology for non-destructive inspection has gained momentum. Lamb waves are guided ultrasonic waves capable of propagating signals over long distance without significant attenuation of signals. The propagation of lamb waves is complicated due to their dispersive and multimode characteristics. The inspection works on the principle that the vibration frequency depends on the material properties and thickness of the pipe. Traditionally, Lamb waves are generated in a plate or a pipe using angled contact transducers. This means that the transducers are held against the plate at an angle. Depending on the angle and the frequency, many different modes can be excited. If a plate has defects, these waves interact (e.g., reflect, scatter, etc.) with these defects; the information about the defect then can be extracted from the propagating waves.

A method of using this technique for real-time and automated monitoring of the pipeline is by using smart materials such as Macro Fiber Composite (MFC) sensors for detecting flaws over a large area of the pipe. The MFC sensors are composed of composite ceramic fibers that can be mounted over the curved surface of the pipe. These sensors can bend and flex when a current is applied to them. They generate a current when they are vibrated or flexed (Jin and Eydgahi, 2008).

Capabilities:

- Can inspect long distances from one single access point and makes it possible to inspect inaccessible areas,
- Saves considerable inspection time compared to other inspection techniques, and
- Can be repeated at intervals of 6 to 12 months to estimate the deterioration of the pipeline with time.

Limitations:

- Does not measure actual wall thickness- just identifies areas of different wall thickness, and
- Best suited for butt welded sections, limited to single spool length tests in cased of flanged, socket-welded and socket and spigot type of pipes.

2.6.8 Wireless Sensor Network (WSN) with Pressure, Acoustic and Water Quality Sensors

Wireless sensors network enables real-time remote monitoring of data collection at different locations along the length of the pipeline. This technique uses advanced sensor node platforms like Intel Mote Sensor Nodes with flash memory and Bluetooth radio. They have the capability for programmable data acquisition configuration, programmable sleep time, reliable data streaming, data processing and programmable data acquisition at the time of triggers. These systems have the capability to monitor hydraulic and water quality monitoring of transmission lines including capturing the pressure transient and water pH. It can also measure pressure and flow velocity for detecting bursts and valve failure, acoustic data for detecting small leaks. Leaks typically manifest themselves in the acoustic signal as relatively high-magnitude noise in frequency bands that are characteristic of the type and placement of the pipe. These characteristic noises, which propagate uniformly in both directions away from the leak, are generated by escaping water flowing through the rupture in the pipeline. Data from sensors at different locations are analyzed to isolate the location of leaks in the pipelines (Stoianov et al., 2007).

Capabilities:

- Automated detection of leaks and bursts with few false alarms,
- Inexpensive to produce, install and maintain,
- High frequency data collection,
- Ability to differentiate between sensor and system faults, and
- Applicability to long range of pipe materials.

Limitations:

- Provides point data and not continuous data along the pipeline,
- Would need high end processors for the analysis of data and provide accelerated responses, and
- This technology is still under development and requires more data to substantiate its performance.

2.6.9 MISE-Pipe: Magnetic Induction Sensors with Wireless Network

This technique has two layers of sensors, the hub layer and the in-soil sensor. The hub layer consists of pressure sensors and acoustic sensors that are deployed inside the pipe near the valves or pump stations. The acoustic sensors can act as a complement to pressure sensors and they can locate the small leaks on the pipeline that could be developed near the checkpoint, valves and near pump stations. The in-soil sensor layer consists of different soil property sensors that are installed on the surface of the pipe and measures the external soil parameters that influence the pipe. The inside layer of sensors communicate with the outside soil sensors through magnetic induction transceivers. This data is transferred to the above-ground appurtenance gateway through wire or wirelessly.

MISE is a transient based leak detection system and by calibrating the transient simulation model based on the pressure model the pipeline network operators can identify some liable areas where the pipeline is prone to have leakage. This would form the first phase of leakage detection using this technique. In the second phase the administrator sends out signals to the pressure, which in turn notifies the soil property sensors in these identified leakage prone areas. Before receiving the notifications these soil sensors will be in sleep mode. Now, the soil sensors are activated and they would gather the pertinent soil property data which is send to the processing hubs via the pressure sensors (Sun et al., 2010).

Capabilities:

- Measures both the internal and external parameters pertaining to the pipe, and
- Soil data is only collected in the areas that are prior identified to be susceptible to failure. This avoids the chances of the users being overwhelmed with less significant data.

Limitations:

- Provides point data and not continuous data along the pipeline, and
- This technology is still under development and requires more data to substantiate its performance.

2.7 Structural Inspection and Monitoring Techniques for PCCP

The different structural inspection and monitoring techniques for PCCP are described in this section.

2.7.1 Array of Hydrophones

This technique uses a number of hydrophones, connected in series which are developed to operate underwater in a pressurized environment. The hydrophones are placed in the water at regular intervals and they continuously monitor for the acoustic events that exhibit the properties of a pre-stressed wire failure. The acoustic events are recorded using a data acquisition system and is checked against a pre-set acoustic design criteria. Wire breaks have a characteristic form which is readily distinguishable from other noises that might be encountered in the pipe. When the relayed signals match that of a wire failure the exact location of it is determined taking into account the speed of sound in water and the spacing of hydrophones (Travers, 1997).

Capabilities:

- This system has been extensively used and proven to be effective on water pipelines, and
- Can be attached to hydrants or other convenient fittings.

Limitations:

- Hydrophones are difficult to use if the pipe is buried deep in the ground, and
- The soil characteristics play a great role in reducing the intensity of the sound. The sound loses intensity faster in clay when compared to sand.

2.7.2 Remote Field Inspection

The basic principle of Remote Field Inspection is based on eddy current technique discussed previously. In PCCP pipes the basic remote field effect interacts with a second, transformer coupling between the coils that produce the A.C. magnetic field and the loops of pre-stressing wire around the pipe. The concrete and mortar of PCCP pipes are transparent to the technique, while the steel cylinder in the pipes provides the metal tube that is necessary for the remote field effect to work. The equipment has a transmitter which produces an electromagnetic field. This is amplified by the pre-stressed wire in the pipe and is recorded by a receiving device. If there are broken wires the received signal will be distorted and a measurement of the distortion can quantify the number of broken wires in the pipe.

The technique can detect the presence of a single broken wire loop in this type of pipe and can differentiate between groups of approximately five breaks – i.e. a single wire break can be differentiated from a group of five wire breaks but not from a pair of wire breaks(Mergelas and Kong, 2001; Yang et al., 2009).

Capabilities:

- Able to produce a complete record of damage to a section of PCCP pipe and of directly detecting broken pre-stressing wires, and
- Unmanned devices are available which avoids the risk of confined space entry.

Limitations:

- If the pipe is not exposed, dewatering of the pipes that have been temporarily taken out of service is required.

2.7.3 Fiber Optic Sensors based on Acoustic Emission Monitoring

For the acoustic monitoring of the PCCP we can use fiber optic sensors. These sensors have the acoustic sensing capability along the length of the cable. When an acoustic wave is produced in the pipe, it travels through the pipe wall and the water column inside the pipeline. These signals impart a stress wave on the fiber. When a beam of light that is propagated through the optical fiber encounters this changing stress field, the light is dynamically reflected. This dynamically reflected light is returned to the receiving station and is analyzed by the data acquisition system. Algorithms are established in the data processing unit which can locate the wire break within 5 feet.

These fiber optic cables are generally installed to the inside surface of the PCCP pipe. Similar to hydrophones the fiber optic sensors record the acoustic events. These events are transmitted to the data acquisition systems where the event is compared against acoustic criteria for a wire break. This comparison is continuously performed by using software and hardware filtering procedures. If an acoustic event passes this filtering process, it possesses the basic acoustic characteristics of wire break and this data is evaluated in detail by experts trained in signal processing. Acoustic Monitoring can be used in short-term and long-term monitoring programs. Unlike other acoustic monitoring techniques the chances of signal weakening is minimal in the fiber optic sensors (Higgins and Paulson, 2006; Lenghi et al., 2008)

Capabilities:

- The sensing cable is always at most one diameter away from the wire break event,
- One sensor and data acquisition unit can be used to monitor up to 12.4 miles of pipe, and
- Attenuation of signals from an acoustic event is minimal as the fiber optic sensors are transmitting light.

Limitations:

- Chances of wire losing the bondage with the pipe surface and floating inside the pipe,
- Chances for the less significant signals to mask the significant wire breaks, and
- Sensors and data acquisition are expensive when compared with other techniques.

Table 2.1 Monitoring Technology and Sensing Characteristics

Monitoring Technology	Parameter	Accuracy	Design Life	Range (Distance between access points)
FBG	Strain	< 2 με	>30 years	30
BOTDA	Strain	± 2 με	>30 years	30-40 miles
MFL	Wall thickness	±8% (Depth)	50 hours standard (at a time)	250 miles standard
RFEC	Wall thickness	< ±10 % (Depth)	50- 60 hours (at a time)	-
US	Wall thickness	< ± 10 % (Depth)	-	-
WSN	Leak detection	< 1 feet	>2 years	-

Table 2.1 - Continued

Hydrophones	Wire break	1/1000th of sec (location)	-	> 1000 ft apart
Remote Field Inspection	Wire break	-	50-60 hours standard	-
AEM	Wire break	Within 5 ft (location)	>30 years	~13 miles

2.8 Leak Detection Technologies

The different leak detection technologies available for SP and PCCP are described in this section.

2.8.1 Acoustic Leak Detection System

When water leaks from a pressurized water pipeline this produces a sound that travels through the pipe wall and the water column. The magnitude and frequency of the noise will depend on a number of factors including the shape and size of the leak, the pipe material and the pressure inside the pipe. The highly sensitive acoustic sensor unit can be inserted into the tap point – 2 inches or greater in diameter while the pipeline is under pressure between 3 and 200 psi. The insertion allows the cable to be inserted into a live main and the retracted guide protects the cable from damage as it passes into the pipe. A winch and cable drum control the deployment and retrieval of the system.

As the system travels through the pipe, the detector head continuously listens for the distinctive noise of a leak that is generated by the escape of under-pressure water. Once the leak has been detected, the sensor head can be stopped at the precise location of the leak. The magnitude of the leak is then estimated by the operator through quantification of the acoustic signal recorded by the sensor. The location of the leak which is now the same as the sensor is located on the surface by a locator unit. This point is accurately marked for subsequent excavation and repair (Mergelas and Henrich, 2005).

Capabilities:

- Can measure leaks as small as 0.25 gallons/hr, and
- Can be used without dewatering the pipeline.

Limitations:

- The profile and layout of the pipe can limit the length of the pipe that can be surveyed, and
- It becomes difficult to use if the pipe is buried deep or in no accessible areas where the surface locator cannot reach the sensor.

2.8.2 Leak Detection using Fiber Optical Sensors

This technique is based on temperature measurements using distributed fiber optic sensing technology and can be used to detect water leaks. The temperature of water is very close to the surrounding air temperature and hence identifying water leaks would need a very sensitive sensor cable. Using the temperature measurements the system can not only detect leakage but with calibration and advanced interpretation algorithms employed by the data acquisition systems, it can qualify the leaks.

In order to design an effective fiber optic based leak detection system there are number of factors that must be taken into account

- Design sensing cables to maximize thermal response while offering sufficient protection to the sensing fiber,
- Positioning of the sensing cable so that is will measure the thermal effects of leak without being effected by temperature surrounding changes. The temperature changes in the surroundings will be filtered for in the data analyzing software in order to avoid false alarms,
- Installation methodology to minimize disruption to pipe-laying operations, and
- System integration with operator’s control system (e.g. SCADA, DCS).

The leak detection cables are installed at the bottom or adjacent of the pipe and measurements are taken every 3-15 feet along the cable length. The system can be used on long distances with repeater stations situated every 40 miles along the pipeline. This would provide full coverage of the pipeline with capability to pinpoint leaks within 3 feet. The additional capacity available in cables can also support telecommunications and SCADA and other ancillary components.

Capabilities:

- Extremely sensitive and able to detect leaks of less than 0.25 gallons,

- Provides continuous monitors at all points along the pipeline at all times, providing complete pipeline integrity,
- The sensing cable is based on passive sensing cables with a design life of over 30 years and maintenance costs are minimal,
- System is fully automated and so lowers operating costs with less risk of human error,
- Can interface with existing SCADA and industrial control system, and
- Ability to locate the leak within 3 feet, thereby reducing the response time and any potential excavation expenses in order to find and repair the leak.

Limitations:

- Sophisticated instrumentation and signal processing are required.

2.9 Third Party Intrusion Monitoring Technologies

The different third party intrusion detection technologies for both SP and PCCP are discussed in this section.

2.9.1 Acoustic Emission Monitoring

This method employs monitoring an in-ground pipeline by detecting an occurrence of a contact with an in-ground pipeline via two different sensors. The system includes a sensor, such as in the form of an accelerometer, in contact with the pipeline segment which would transmit the signals which would be conditioned and processed by another unit at a distance. These sensors have the capability of detecting the vibrations associated with 3rd party intrusions. The second impressed current sensor in the form of a current pick-up line has a transmission station which transmits the signals and is received by the receiving station. The third party intrusion will be sensed by both the sensors. The signals from the acoustic sensor and the impressed current sensor will receive the processing unit at different times and known respective speeds which enable the determination of the location of contact on the pipelines.

Another solution available is a system with acoustic impact detection sensors for providing real time monitoring against third party damage. The system is comprises of series of acoustic sensors, power supplies and remote transmitting devices which are placed along the pipeline at fixed intervals. When a piece of equipment, such as the shovel of a backhoe, strikes the pipeline, the sound generated travels through the pipe to the nearest acoustic sensor in both directions. The sensor's electronics filters analyzes the sound to determine exact location and if an alarm is warranted. If the sound meets the alarm criteria, a radio alert is transmitted to operations personnel or the monitoring service. The acoustic sensors transmitting the alert will also identify the location of the strike to facilitate rapid intervention (Haines and Francini, 2003).

Capabilities:

- This system does not require any signal to be applied on the pipeline,
- Potential detection of other significant conditions such as leaks or product theft, and
- Sensors can be placed at 10 miles intervals.

Limitations:

- The system does not have the capability to differentiate vibrations from third party intrusions and valve closures or routine maintenance operations,
- This system has reduced sensitivity to damaging contacts from boring and drilling tools, and
- Require sophisticated filtering techniques to reach acceptable signal/noise performance.

2.9.2 Impressed Alternating Cycle Current (IACC)

This pipeline monitoring method sends electrical signals on the pipe by generating a time-varying voltage between the pipe and the soil at locations where pipeline access is available—normally, cathodic protection (CP) test points. These signals travel in both directions from the transmission point and the receiving stations at a designated distance will continuously monitor the received signals by measuring the pipe-to-soil waveform. Third-party contact to the pipe that breaks through the coating changes the waveform of the signals received at the IACC receiving stations. This enables the users to locate the segment of intrusion. The advantage of the system is that the location of the transmission and receiving stations can be same as the cathodic protection points and this gives access to power for running the system (Burkhardt and Crouch, 2005).

Capabilities:

- Detects contact from backhoe strike as well as from boring tools and drills,
- Does not require digging to attach sensor; attachment is made through existing cathodic test point, thus allowing low-cost retrofitting of existing pipelines, and
- Can be temporarily applied for short-term monitoring of construction intense areas.

Limitations:

- Short Detection range (less than 10 miles),
- Sensitivity may be reduced by breaches in pipe coating, and
- May have interference from cathodic protection systems.

2.9.3 Fiber Optic System (3rd party intrusion using OTDR)

Fiber Optic sensors are sensitive to stress and vibrations applied to the fiber and this is reflected as changes in the fiber's light transmission. This change may be detected and located by using optical time domain reflectometry (OTDR). Unused singlemode fibers within the fiber optic communication cables can be used for this purpose or new fiber optic cables are attached to the surface of the pipeline. Light signals are periodically sent through the fiber optic sensors, and the reflected light is recorded back at the source. When heavy equipment is within the right of way, it compresses the soil and creates vibrations which change the dynamic of the light and reflect those changes back to the source. Using a custom designed optical time domain reflectometer, which is able to measure the reflected light and accurately interpret the signal, the system objective was to identify a target and determine its status as hazardous or minor. If the signal is determined to be hazardous, an alarm is triggered. The speed of light is known and this enables the system to pinpoint the exact location of the intrusion and notify the operator for a response.

Another solution could be a fiber optic cable laid in close proximity above, or adjacent to (within 3 to 9 feet) the pipeline which would enable the detection of intrusion even before it reaches the pipeline and damages its coating and cuts the fiber optic cable. These systems are very sensitive to ground movements and the frequencies of the sound or pressure waves generated by the intrusive equipment.

This gives the user a higher response time to the user and avoids the need of repairing the optic cables during each incident (Cauchi et al., 2007; Huebler, 2002; Burkhardt and Crouch, 2005).

Capabilities:

- Continuous real time monitoring,
- Can protect 25 miles of pipeline with a single system,
- Ability to detect and locate simultaneous encroachments at different locations along the pipeline,
- Ability to monitor earthquakes, landslides, floods or stream scour, and
- The additional capacity within the cables can be used for telecommunication, SCADA, etc.

Limitations:

- Fiber must be installed in the right-of-way,
- Signals from minor pipe-loading events may mask the rare significant event, and
- Sophisticated instrumentation and signal processing are required.

The above provided list of techniques clearly indicates the wide range of techniques that are available in the industry for pipeline inspection and monitoring. This corroborates the fact that a detailed analysis is required for the selection of an appropriate method for the monitoring of a pipeline.

2.10 Chapter Summary

To avoid catastrophic failures, pipeline operators need to monitor integrity of their pipelines. Several solutions are available for the pipeline failure prevention and leak detection. A comprehensive research on the available techniques, their capabilities to detect, localize and report the structural defects, leaks, bursts and third party intrusions were presented in this chapter. The objective of this chapter was to present the characteristics of each of these techniques to enable a comparative study.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the methodology adopted for this research. An overview of the methodology was presented in Chapter 1. The primary interest is in large diameter water transmission pipelines. Steel and PCCP pipes are considered for the evaluation of pipeline inspection and monitoring techniques. In order to predict and mitigate the pipeline failure, the pipeline operator should choose the technique based on the critical parameters that govern pipe performance. For this purpose a condition assessability index was calculated for each of the alternative techniques.

Condition assessability index defines the technical feasibility of inspection technologies to monitor the failure indicators thereby assisting in preventing structural failure (Kola, 2010). This index takes into account the capability of a technology to quantify the pipe condition and predict the impending failure in a timely manner. The procedure for calculating the condition assessability index involved two steps:

i. Gather knowledge about the various technologies and methodologies presently being used or/and being developed in the industry for pipeline monitoring.
ii. Establish relationship between the distress indicators of pipelines with the technologies which can detect them.

A detailed breakdown of the steps employed in this research is explained in *Figure 3.1*.

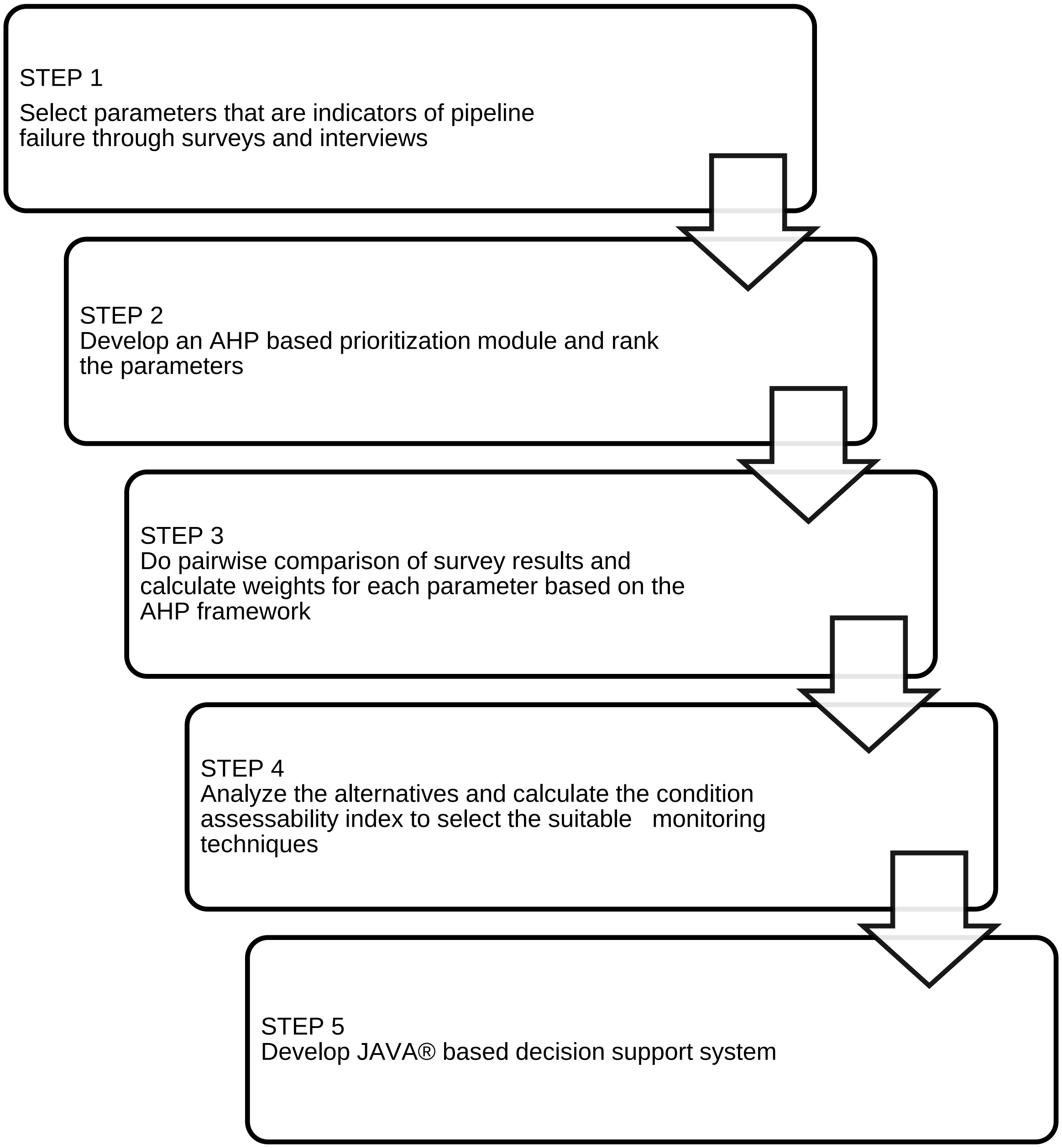


Figure 3.1 Methodology of the Study

3.2 Selection and Prioritization of Pipeline Monitoring Parameters

This section discusses in detail the different steps adopted for the selection and prioritization of pipeline monitoring parameters.

3.2.1 Step 1: Identification of parameters

For pipe materials under consideration in this study, the task of selecting suitable monitoring parameters has been approached by considering the informational needs of the pipeline operator, in conjunction with the likely modes of failure. A failure type is defined as the final manifestation of the damage at the time of failure and this includes holes, blow-out, circumferential, spiral and longitudinal breaks and cracks, joint failures such as pulled-out joints, split bells, bell shears etc. The causes of failure mostly concern the underlying reason that lead to the failure such as corrosion, loads and stresses, internal pressure, third party damage etc. A pre-failure damage type is defined as the initial manifestation of structural deterioration that in the future could lead to failure through one of the identified failure types. Pre-failure damage indicators are parameters which can be monitored, that indicate a structural deterioration. Preventing catastrophic failure through improved monitoring involves the identification of most probable damage indicators that can be monitored and accessed at an earlier stage so as to proactively prevent the gradual onset of failure. Such pre-failure damage indicators include leakage rate, movement patterns in the pipe and soil, changes in the electrical, magnetic, electromagnetic and acoustic properties of the pipe system (pipe, liner and coating). Such indicators can be broadly classified as global, local and environmental parameters

3.2.1.1 Global Parameters

Global parameters give indication of general pipeline conditions which when combined with data from other monitoring and condition assessment techniques gives a complete picture of the integrity of the pipeline. This would assist in the prioritization and selection of appropriate rehabilitation and renewal techniques. The different global parameters considered in this study include:

Internal Water Pressure: Working pressure is defined as the maximum internal pressure under steady state conditions for each pipe, or portion of the pipeline, established by the hydraulic grade line. The predicted operating pressure cycle will have been considered at the hydraulic design stage. The pressure class of the steel pipe is set at or above the working pressure. It is recognized that a pipe’s integrity is influenced more by the size and rate of pressure cycles rather than the operating pressure. Changes from predicted operating pressure cycles could lead to premature failure. Monitoring of internal pressure can help the operator in locating leaks.

Transient Pressure: A transient pressure in a pipeline is a generic term for a wave phenomenon that accompanies a rapid change of the velocity of the fluid in the pipeline. Pressure transients can be positive or negative. Surge pressure is generally used to denote a transient pressure that might last for several minutes (Fleming et al, 2006). This has no detrimental effect on the pipe in short term but the severity and frequency of pressure surges will affect the fatigue life of pipe. Water hammer is used to denote a sudden transient pressure that will have serious consequences on the pipe if not properly addressed and mitigated. The magnitude of these surges is independent of the operating pressure, and can be many times normal operating pressure. The duration of a transient pressure will vary from several minutes in relatively long pipe segments, to several hundredths of a second in the case of water hammer events. This water pressure fluctuation causes radial stress and fatigues.

External Loads on the Pipe: External loads are defined as all live and dead loads applied to the outside of the pipe after installation. Dead loads are the pipe weight, water weight, and all superimposed static loads, including earth loads, applied to the outside of the pipe after installation. Live loads are defined as all external transient loads applied to the outside of the pipe during and after installation. Pipes are designed to resist buckling from external loads. Other live loads include construction loads from future construction activity in the pipeline vicinity.

Pipe Wall Thinning: Pipe wall thinning is one of the pre-failure damage indicators that indicate structural deterioration. In steel pipes, this gives a significant indication of corrosion. This is a critical factor in case of steel pipes as steel pipes, are generally thinner when compared to other pipes like cast iron or ductile iron pipes which generally have a sacrificial thickness assigned during design. In case of PCCP pipes thinning this is generally not a critical indicator.

Third Party Intrusion: Interference from third party activities can result in impact damage, damage to the pipe sleeving, and excessive pipe loading. Damage to pipe from digging and other activities in the vicinity of the pipe can lead to pipe failure.

3.2.1.2 Local Parameters

Local parameters give indication of the localized problems which could lead to potential failure. This data when combined with all the other data would assist in predicting the susceptible segments in the pipeline. The different local parameters considered in this study include:

Pipeline Leaks: seam leaks and pin hole leaks: Leakage is usually the major cause of water loss. There are many possible causes of leaks, and often a combination of factors lead to their occurrence. The material, composition, age, and joining methods of pipes and appurtenances can influence leaks. Causes of leaks include corrosion, cracks, material defects or failure due to deterioration over time, faulty installation, inadequate corrosion protection, ground movement over time due to drought or freezing, and repeated excessive loads and vibration from road traffic. Old pipes often leak substantial amounts of water through corroded areas, cracks, and loose joints. Leaks that go unnoticed can cause gradual bedding erosion and detectable excess strain.

Pipe Corrosion: Corrosion is an electrochemical process, which requires a potential difference between two points that are electrically connected. For a pipe containing metal buried in soil, the soil acts as the electrolyte and the electrons flow from the anodic area through the soil to the cathodic area and back through the metal in the pipe to complete the circuit. Corrosion can be external or internal, caused by aggressive water or microbes, stray currents, oxygen gradients and bimetallic connections. In steel pipes corrosion occurs in the form of thinning and/or pitting at locations where protective linings or coatings are not used or are not intact. Two corrosion parameters to be monitored in steel are – (i) length of corrosion in the longitudinal direction and (ii) the extent to which it has penetrated the wall thickness. In PCCP pipes corrosion effects the steel wires which lose its pre-stressing and the concrete will no longer remain in compression.

Strain Measurement: Strain is a measurement of primary deformation of the pipe as a function of internal or external stresses. In general, the forces applied to buried pipe can be considered as five kinds: those produced by internal pressure; bending forces; crushing forces; soil movement induced tensile forces; and temperature induced expansive forces. These forces will be expressed as strain on the steel pipe.

Pre-stressing Wire Break: PCCP pipes are designed so that the level of pre-stressing will counter the tensile stresses induced under normal operations. Corrosion of the steel reinforcements in the concrete occurs at high rates when the pH of concrete adjacent to the steel locally reached lower values. Cathodic protection has been applied to PCCP water pipes in the past, but this could cause hydrogen embrittlement of pre-stressing wires and subsequent pipe rupture.

Pipe Deformation: Flexible coated steel pipe shall be designed to deflect less than 2%. Mortar coated steel pipe shall be designed to deflect less than 1%. When the depth of cover is such that the deflection becomes larger than the values stated above, the embedment design shall be improved to limit deflection.

3.2.1.3 Environmental Parameters

Deterioration of pipeline wall structure when reaches a point where it can no longer endure the internal pressure or external load, it leads to local failures. The impact of environmental parameters can vary with the type of pipe material. Although these parameters do not give a direct indication of the structural condition of the pipeline, they can act as early warning indicators to highlight high risk areas. The different environmental parameters included in this study include:

Soil Corrosivity: Soil conductivity depends on many factors, such as degree of consolidation, salt content, organic matter, moisture, etc. Moisture content is one of the important variables in soil resistivity. As the moisture content increases the resistivity drops rapidly. The factors that affect the corrosivity of soil are soil-water-air proportion, soil resistivity and pH of the soil. The low pH in the soil around PCCP pipe lowers the pH of the cement mortar to a point where corrosion of the pre-stressed wire will occur, resulting in substantial weakening of the pipe. Similar is the case of steel pipes with cement mortar coating.

Water Quality and pH: The various water quality parameters that are expected to influence corrosion include pH, alkalinity, and buffer intensity. Other factors include dissolved oxygen, types of scales formed, and presence of corrosion inducing microbes.

Ground Stability: This is an indicator of the pipe soil movement. Some of the factors that influence ground stability are proximity to liquefaction areas, expansive clay, landslide prone areas, seismic activity prone areas, etc. The landslide and earthquake can cause circumferential failure of the pipe. These factors affect the structural loading, causes circumferential rupture due to landslide, leading to possible failure.

Flood Risk Potential: This parameter takes into account the buoyancy effect, tidal effect, current effects, and scouring. This is significant at locations where the pipe crosses streams and rivers. Excessive scouring can lead to pipe exposure which increases the risk of pipe failure and alteration of the natural substrate of the watercourse. If the buoyancy control provides to be inadequate, the pipe will float and have to be repaired.

All the parameters have to have significant influence on the pipeline structural performance. *Table 3.1* presents a comprehensive overview of why each of these parameters should be monitored. The next step in this study is to prioritize of each of these parameters in the order of their capability to indicate impending pipe failure. This is accomplished is step 2 of this study.

Table 3.1 Critical Damage Level Factors

Parameter	Why Monitor?
Internal water pressure	Could assist in the detection of bursts. Record cyclic loading behavior
External loading on Pipe	Need to monitor to identify changes in loading
Pipe wall thinning	Provides indication of residual strength and time to through wall corrosion
Third party intrusion	May affect integrity of the pipeline. Includes direct damage to pipeline and changes in environment that could lead to pipe deterioration or changes in structural loading causing displacement
Pipe leakage	Clear indication of pipe barrel or joint failure
Pipe Corrosion	Affects the integrity of the pipe
Strain measurement/Wire breaks	Affects the integrity of the pipe
Pipe deformation	Risk of failure
Soil corrosivity	Affects corrosion rate
Water quality and pH	Could affect corrosion rate and bacterial growth
Ground stability	Affects structural loading, leading to possible failure
Flood risk potential	Affects structural loading

3.2.2 Step 2: Prioritization of Pre-failure Indicators

In this step the damage level indicators are prioritized using Analytical Hierarchy Process. Analytical Hierarchy Process (AHP), developed by Thomas Saaty, addresses how to determine the relative importance of a set of activities in a multi-criteria decision problem. The process makes it possible to incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria.

This framework is most suitable for this study as it addresses the determination of the relative importance of a set of alternatives in a multi-criteria decision problem. This process makes it possible to incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria. The AHP method is based on three principles: (i) structure of the model, (ii) comparative judgment of the alternatives and the criteria; (iii) synthesis of the priorities (Saaty,1994).

To make a decision in an organized way to generate priorities we need to organize the decision making process into the following steps:

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).
3. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

Based on the identified risk factors in step 3, a hierarchical risk model is developed. *Figure 3.2* shows the AHP framework for the risk structure. The hierarchy has four levels: overall goal of the problem is the first level. The factors and sub factors form the second and third level. These factors and sub-factors were identified in step 1 of the study. The fourth level is the alternatives; in this case the different pipeline monitoring techniques form this level. The alternatives were discussed in detail in chapter 2.

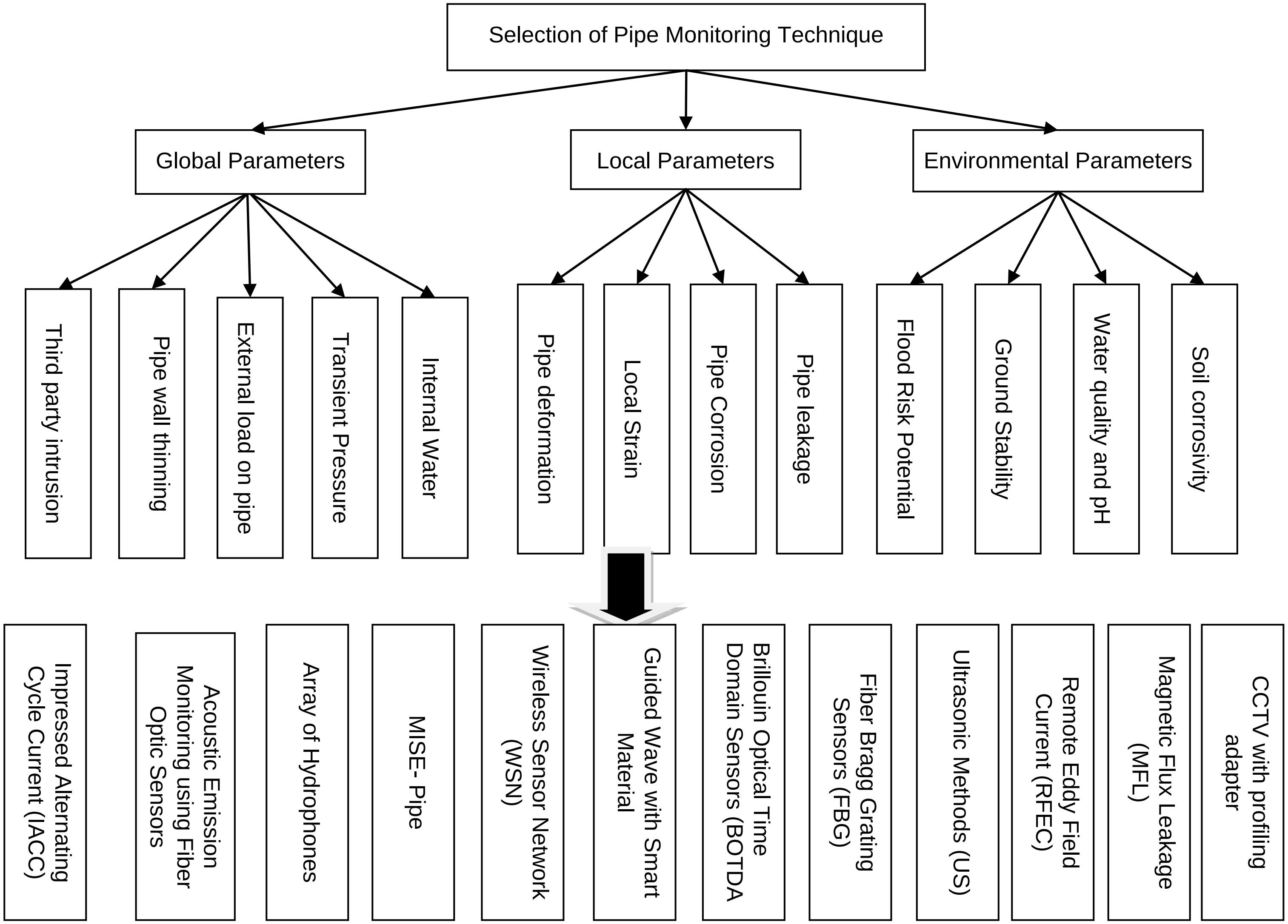


Figure 3.2 *Analytical Hierarchy Process Model*

3.2.3 Step 3: Pairwise Comparison of Parameters

In step 2, the problem has been decomposed and the hierarchy is constructed. In this step the prioritization procedure starts in order to determine the relative importance of the criteria within each level. The pairwise comparison is conducted for the factors and sub factors to determine the probability of pipeline failure. In each level, the criteria are compared pairwise according to their levels of influence and based on the specified criteria in the higher level. In Analytical Hierarchy Process (AHP), multiple pairwise comparisons are based on a standardized comparison scale of nine points. Refer Appendix B for the sample questionnaire. *Table 3.2* shows the comparison scale.

Table 3.2 Scale of relative importance for pair-wise comparison
Source: (Saaty, 1994)

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the object
3	Moderate importance	Slightly favors one over another
5	Essential or strong importance	Strongly favors one over another
7	Demonstrated importance	Dominance of the demonstrated in practice
9	Extreme importance	Evidence favoring one over another of highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

Surveys and interviews were conducted to perform the pairwise comparison of the factors and sub-factors. The surveys were sent out to 46 professionals in the pipeline industry, who were asked to respond to the questions based on their experience in the pipeline design and operation. The professionals were selected based on their experience working with large diameter water transmission pipelines. It was ensured that the survey participants belonged to various sections of the pipeline industry. This enabled the research to include the perceptive from the view of pipeline operator, project manager but also engineers, designers, and pipeline manufacturers.

The survey was sent out through e-mail to each of the participants and the response was also received through e-mail. The response rate to the questionnaire was 48%. 4 interviews were conducted with the pipeline designers. The survey asked the responders to perform pairwise comparison of the factors and sub-factors using the Saaty's 1-9 scale. The participants compared the parameters in pairs to judge which of each parameter is preferred over the other. Please refer to Appendix B for the sample survey questionnaire.

Every expert answered the survey individually and then the geometrical mean (GMM) of the response was calculated and a single matrix was formed. This matrix was normalized and the consistency rates were calculated. All the consistency rates were less than 0.1. The weights of the factors and sub-factors were calculated and then these weights are multiplied, to calculate the resultant weights. The analysis of the AHP was conducted by using Microsoft Excel® spreadsheet.

As an illustrative example consider the following judgment matrix shown in Table 3.3 formed from the survey results for global parameters.

Table 3.3 Judgment Matrix for Global Parameter obtained from Survey Results

Sub-factors	Internal Water Pressure	Transient Pressure	External Loading	Pipe Wall Thinning	3rd Party Intrusion
Internal Water Pressure	1	5/7	2 3/8	1 1/9	1 3/8
Transient Pressure	1 3/8	1	3	1 1/2	2
External Loading	3/7	1/3	1	4/9	4/7
Pipe Wall Thinning	8/9	2/3	2 1/4	1	1 1/7
3rd Party Intrusion	5/7	1/2	1 1/2	7/8	1
Sum of Columns	4.42	3.24	10.04	4.97	6.01

The next step is to extract the relative importance implied by the previous comparisons. This is achieved by estimating the right principal eigenvector of the previous matrix. Given a judgment matrix with pairwise comparisons, the corresponding maximum left eigenvector is approximated by normalizing the elements in each column of the matrix and then averaging over each row. That is, the each element in the column divided by the sum of the elements in the column. Next the numbers are normalized by calculating the average of each element in the row.

In the AHP the pairwise comparisons in a judgment matrix are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% (Saaty, 1994). The CR coefficient is calculated as follows. The first step is to estimate the consistency index (CI). This is done by adding the columns in the judgment matrix and multiply the resulting vector by the vector of priorities (i.e., the approximated eigenvector) obtained earlier. This yields an approximation of the maximum eigenvalue, denoted by λ_{max}. Then, the CI value is calculated by using the formula: $CI = (\lambda_{max} - n)/(n - 1)$. Next the consistency ratio CR is obtained by dividing the CI value by the Random Consistency index (RCI) as given in *Table 3.4*.

Table 3.4 RCI values for different values of n

n	1	2	3	4	5	6	7	8	9	10	11
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

When these approximations are applied to the previous judgment matrix it can be verified that the following are derived: $\lambda_{max} = 4.976$, CI = -0.006, and CR = -0.0054. Since the CR value is less than 0.1 the pairwise comparison matrix satisfies the condition. The resultant weight for the sub-factors is a product of weights of factor and weight of sub-factor. The weight of global parameter was derived to be 42%. The resultant weights of the sub-factors of global parameter are as shown in Table 3.5:

Table 3.5 Weight and Resultant Weights for Sub-factors of Global Parameter

Global Parameters	Weight	Resultant Weight
Internal Water Pressure	23%	10%
Transient Pressure	31%	13%
External Loading	10%	4%
Wall Thinning	20%	8%
3rd Party Intrusion	16%	7%

Survey was also conducted among pipeline operators to understand the type of monitoring systems currently in use in the industry and to understand the performance of these techniques. Please refer to Appendix C for the sample questionnaire.

3.2.4 Step 4: Selection of Appropriate Inspection/Monitoring Techniques

In this step, the appropriate monitoring technique for a pipeline monitoring is selected based on the results from the AHP pairwise comparison performed in the previous step 3. *Table 3.6* provides a list of technologies identified for Steel and PCCP pipes and the various distress indicators they can monitor. Based on this table the condition assessability index of each monitoring technique was calculated. The condition assessability index of a technique is the sum of the weights of each of the pre-failure indicator that it can measure. The weight of the parameter was calculated in step 3 for each of the pre-failure indicators.

Table 3.6 Capabilities of Pipeline Inspection and Monitoring Techniques

	Global Parameters					Local Parameters					Environmental Parameters			
Monitoring Technology	Internal water pressure	Transient pressure	External loading	Pipewall thinning	3rd party Intrusion	Pipe Leakage	Corrosion	Strain	Wire break	Deformation	Soil Corrosivity	Ground Stability	Flood risk	Water quality & pH
CCTV with profile adapter	No	No	No	No	No	No	No	No	No	**Yes**	No	No	No	No
Magnetic Flux Leakage(MFL)	No	No	No	**Yes**	No	**Yes**	**Yes**	No	No	No	No	No	No	No
Remote Field Eddy Current/Thermal Coupling(RFEC/TC)	No	No	No	**Yes**	No	No	**Yes**	No	**Yes**	No	No	No	No	No
Ultrasonic Methods (US)	No	No	No	**Yes**	No	No	**Yes**	No	No	No	No	No	No	No
Fiber Bragg Grating (FBG)	No	No	**Yes**	No	**Yes**	No	No	**Yes**	No	**Yes**	No	**Yes**	**Yes**	No
Brillouin Optical Time Domain Sensors (BOTDA)	No	No	**Yes**	No	**Yes**	**Yes**	No	**Yes**	No	**Yes**	No	**Yes**	**Yes**	No
Guided Wave Technology with Smart Materials (GW)	No	No	No	**Yes**	No	No	**Yes**	No	No	No	No	No	No	No
Wireless Sensor Network (WSN)	**Yes**	**Yes**	No	No	No	**Yes**	No	No	No	No	No	No	No	**Yes**
MISE-Pipe	**Yes**	**Yes**	No	No	No	**Yes**	No	No	No	No	**Yes**	No	No	No
Hydrophones	No	No	No	No	No	**Yes**	No	No	**Yes**	No	No	No	No	No
Fiber Optic based Acoustic Emission Monitoring	No	No	No	No	**Yes**	**Yes**	No	No	**Yes**	No	No	No	No	No
Impressed Alternating Cycle Current (IACC)	No	No	No	No	**Yes**	No	**Yes**	No	**Yes**	No	No	No	No	No

3.2.5 Step 5: Decision Support System

This step involves the development of a decision support system that would serve as a guidance tool for selecting the suitable pipeline inspection and monitoring technique for a water transmission pipeline system. The tool was developed using JAVA® and has two modules. The first module is a graphical user interface that gives the user a chance to do a comparative analysis of parameters selected in step 1. The second module contains the backend logic of analytical hierarchy process. In this module the comparative analysis matrix for the user input is developed and the normalized matrix is developed. The eigen values and consistency ratios are calculated. Based on this calculation the weights for each parameter are calculated and the recommendation for the monitoring. This tool can be used by pipeline operators for prioritizing their asset management plan.

3.3 Case Study: Integrated Pipeline Project

Integrated Pipeline Project (IPL), a 150-mile long water transmission pipeline project, is a joint effort between the Tarrant Regional Water District (TRWD) and the City of Dallas. The main objective of partnership is to explore the feasibility of an integrated approach to bring additional water into the Dallas and Tarrant Regional Water District (TRWD) service areas to address the water demand for next 100 years. The project is currently in its preliminary engineering stage. This project was selected to evaluate the condition assessability model and select the most applicable technique for the structural monitoring of the pipeline.

As discussed earlier, the initial in-use phase of pipeline is generally trouble free with low frequency of failure. However, identifying the parameters to monitor and the problem areas on the pipeline during the design phase would enable the pipeline operator to

- Make provisions for pipeline monitoring to be added as and when it is needed.
- Develop an asset management strategy

Table 3.7 shows the various pipeline segments of the IPL Pipeline with the respective lengths and diameters of each segment.

Table 3.7 IPL Project Segment Details Showing the Length and Diameter of Pipe

Segments	Length (feet)	Diameter (inch)
19	220,394	84
17	26,159	108
15	329,388	108
9,11	114,131	84
18	8,517	72
16	57,768	66
12	7,120	108
10	14,765	84

The terrain data is available from the Integration Study conducted at the conceptual phase of this project. Table 3.4 provides the segments of the IPL pipeline and their corresponding lengths. The major classification based on the land type, and crossings. Refer to Appendix D for the terrain details of IPL project segments.

The major two classifications for the land type are rural and urban. Rural area majorly encompasses rural or farmland areas. This classification has been further divided into pasture, croplands and wooded area. Urban area is congested area with conflicts with roads and other structures. Urban areas are further classified into light urban, medium urban and heavy urban.

Crossings include when the pipeline route crosses major topographic features or existing facilities. Open cut crossings are for employed for minor roads which are typical county roads and some city streets with minor vehicle counts. Open cut crossings could be employed for small water bodies such as creeks or ponds that can be dewatered temporarily to facilitate the installation of pipeline. Crossing Tunnels are employed for crossing major roadways, railroads or major utilities which would be tunneled underneath during construction due to the high impact this would have on the area. Deep tunnels are tunnels which run 40 ft to 100 ft deep. These are employed in heavily urbanized areas and areas where the power cost for pumping the water can be reduced by lowering the highest point of the pipeline. The corrosivity of the soil has been analyzed and has been classified as low, medium and high corrosive areas. A project specific analysis based on the prioritized parameters was done to select the critical areas in the pipeline segments.

3.4 Chapter Summary

This chapter presented the methodology that used for this study. A pair-wise comparison survey was conducted among pipeline manufacturers, design engineers and pipeline operators. The results of this survey were used to develop an AHP based model and the weights for each parameter were calculated. These weights were used for the prioritization and selection of appropriate monitoring technique. A JAVA® based software tool with AHP analysis capability was developed and a case study on the IPL project was done to evaluate the critical parameters and monitoring capability of this project.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the results and findings of this research as explained in Chapter 3.

4.2 Analysis of Survey Results

The survey respondents spread over 9 states in the United States as shown in *Figure 4.1*.

Figure 4.1 Map of United States Showing Locations of Survey Respondents

The respondents who answered the survey represented various areas in the pipeline industry. The distribution of the survey participants is presented in *Figure 4.2.*

Figure 4.2 Distribution of Survey Respondents by Position

- The survey results show that the most significant parameters to monitor in a steel pipe are global parameters which include internal water pressure, transient pressure, external loading, pipe wall thinning and third party intrusion.

- *Figure 4.3* shows the weights of global, local and environmental parameters from the AHP Analysis for Steel Pipe.

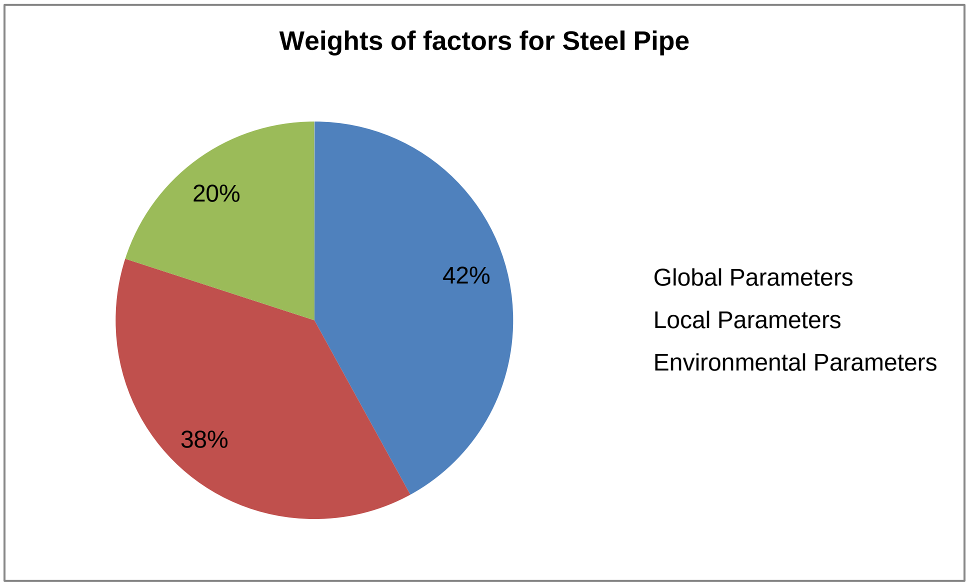


Figure 4.3 Weights of Factors for Steel Pipe

- It was found that the most significant parameters to monitor in a PCCP are local parameters which include pipe leakage, corrosion, pre-stressed wire breaks and corrosion. *Figure 4.4* shows the weights of global, local and environmental parameters from the AHP Analysis for PCCP.

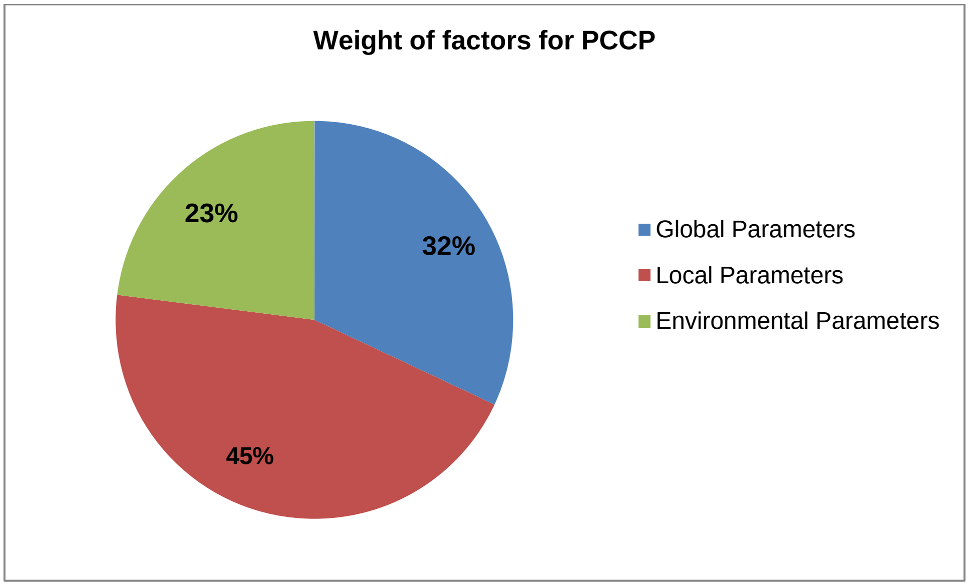


Figure 4.4 Weights for Factors for PCCP

- *Table 4.1* and *Table 4.2* present the results of the AHP analysis for the parameters for steel pipe and PCCP respectively. The individual weights for the factors and sub-factors were both received from the analytical hierarchy process. The resultant weight of each parameter is a product of the weights of individual factors.

Table 4.1 Weight Calculation of Parameters for Steel Pipe

Factor	Factor Weights	Sub-factors	Sub-factors Weight	Resultant Weight[3] (Rounded to nearest percentage)
Global Parameter	42%	Internal water pressure	23%	10%

---

[3] Resultant Weight = Factor weights x Sub-factors weight

Table 4.1 – Continued

		Transient pressure	31%	13%
		External loading	10%	4%
		Pipe wall thinning	20%	8%
		3rd Party intrusion	16%	7%
Local Parameter	38%	Pipe Leakage	20%	8%
		Corrosion	54%	21%
		Strain	11%	4%
		Pipe Deformation	15%	6%
Environmental Parameter	20%	Soil Corrosivity	52%	10%
		Ground Stability	27%	5%
		Flood Risk	9%	2%
		Water quality and pH	12%	2%

Table 4.2 Weight Calculation of Parameters for PCCP

Factor	Weight	Sub-factors	Weight	Resultant Weight
Global Parameter	32%	Internal water pressure	33%	11%
		Transient pressure	33%	11%

Table 4.2 - Continued

		External loading	3%	1%
		Pipe wall thinning	15%	5%
		3rd Party intrusion	15%	5%
Local Parameter	45%	Pipe Leakage	27%	12%
		Corrosion	20%	9%
		Wire Breaks	46%	21%
		Deformation	7%	3%
Environmental Parameter	23%	Soil Corrosivity	46%	11%
		Ground Stability	34%	8%
		Flood Risk	6%	1%
		Water quality and pH	14%	3%

- A majority of the participants agreed that the most important global parameter that needs to be monitored in steel pipes is transient pressure followed by internal water pressure. *Figure 4.5* illustrates the data discussed in *Table 4.1*.

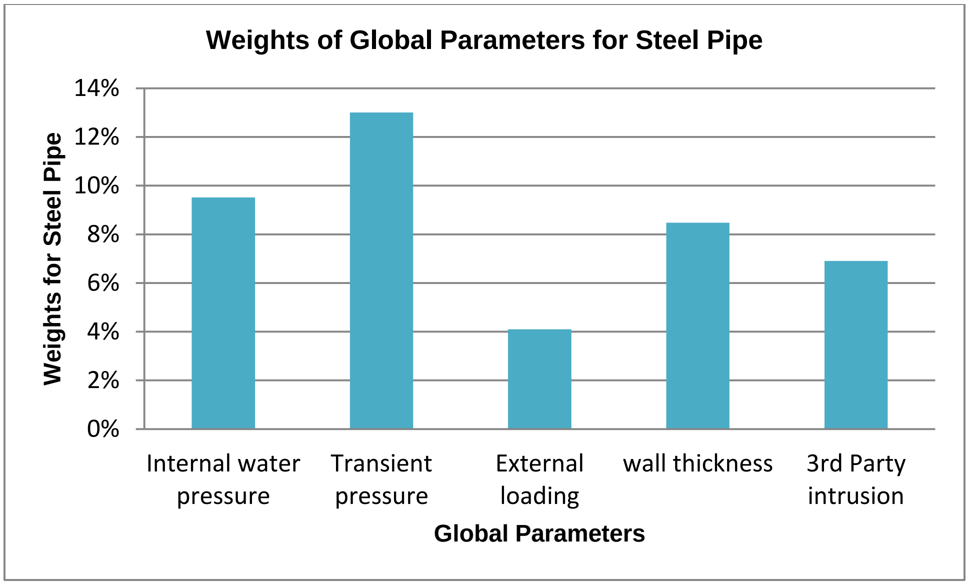


Figure 4.5 Weights Global Parameters for Steel Pipe

- For PCCP both internal water pressure and transient pressure were found to have equal significance and both needs to be monitored to predict the failure of the pipe. .*Figure 4.6* shows the weights of global parameters for PCCP.

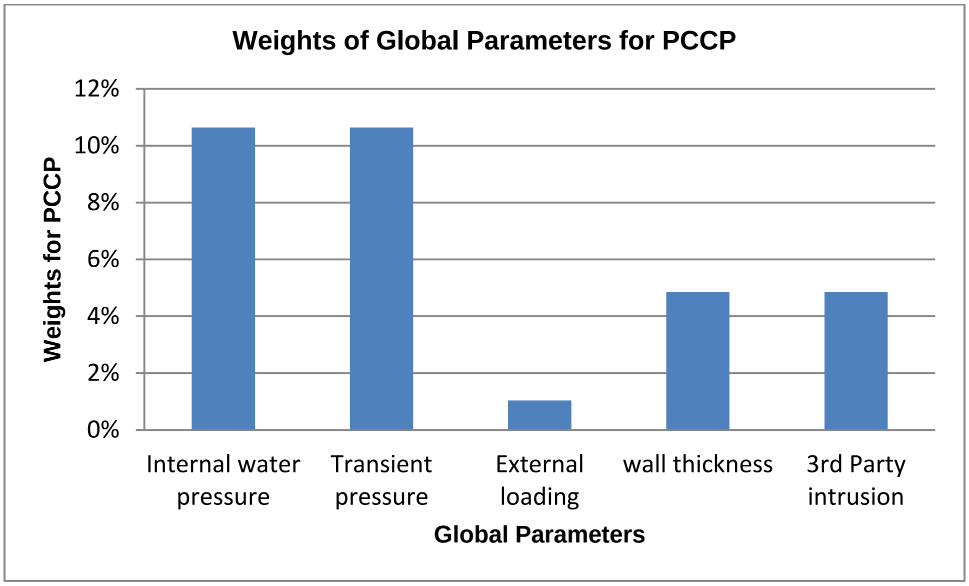


Figure 4.6 Weights for Global Parameters for PCCP

- From the analysis of local parameters, it was found that corrosion is the most significant indicator of pipe failure in steel pipes followed by leaks. The weights of local parameters are shown in *figure 4.7*

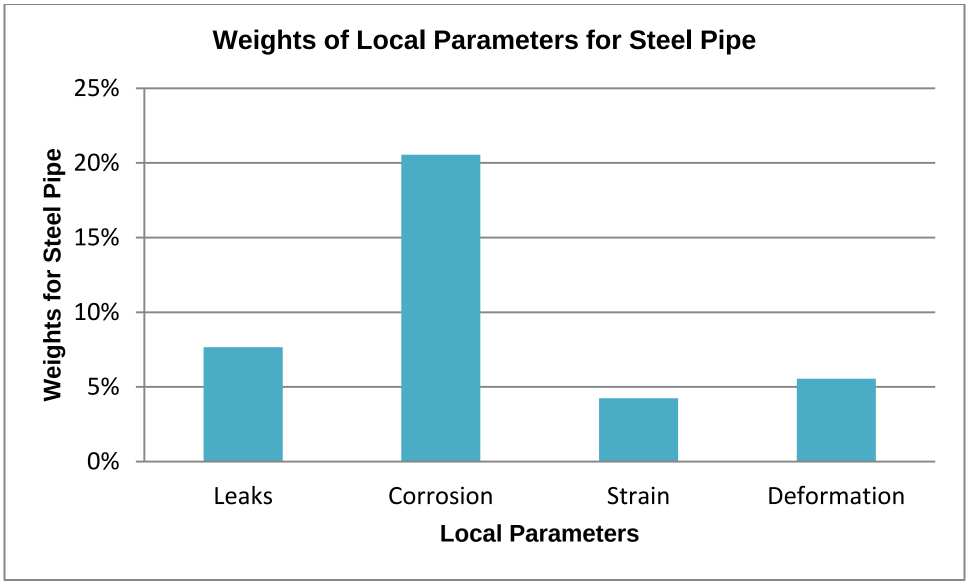


Figure 4.7 Weights of Local Parameters for Steel Pipe

- It was found that for PCCP pre-stressing wire break is the most important factor and needs to be monitored on a long term basis.
- *Figure 4.8* illustrates the weights of local parameters for steel pipes and PCCP.

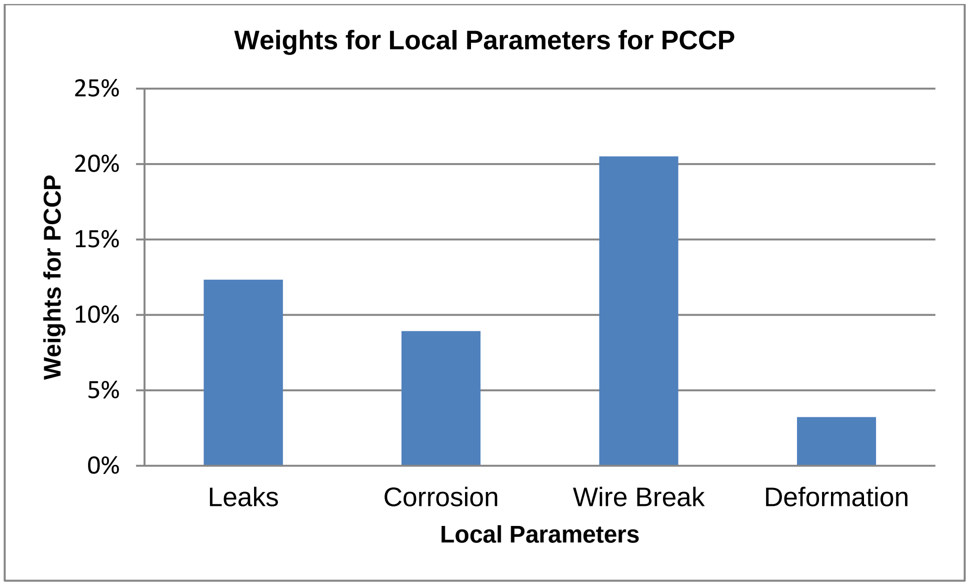


Figure 4.8 Weights for Local Parameters for PCCP

- *Figure 4.9* and *Figure 4.10* show the results for the weights for environmental parameters. For both steel pipe and PCCP it was found that the environmental parameter that is most critical is soil corrosivity followed by ground stability.

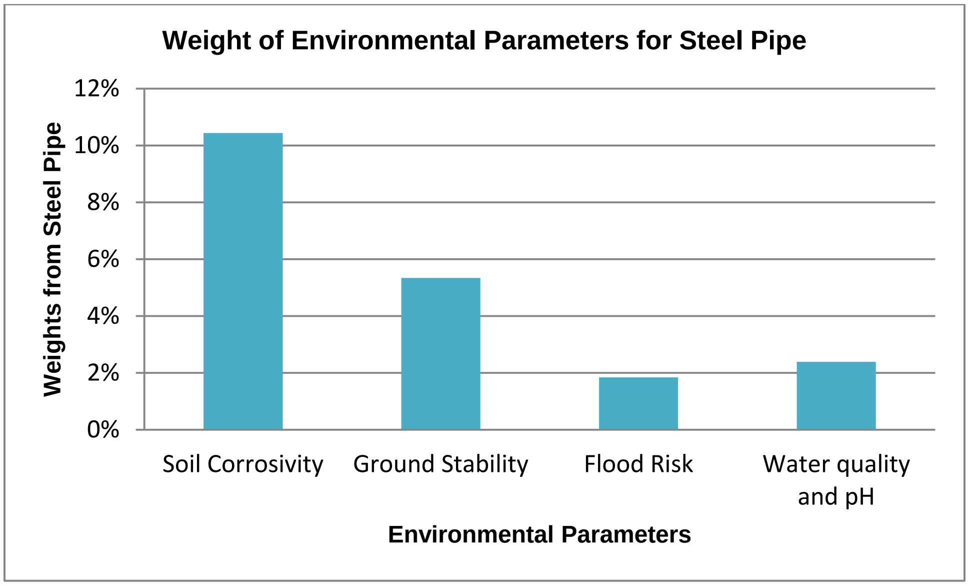


Figure 4.9 Weights for Environmental Parameters for Steel Pipe

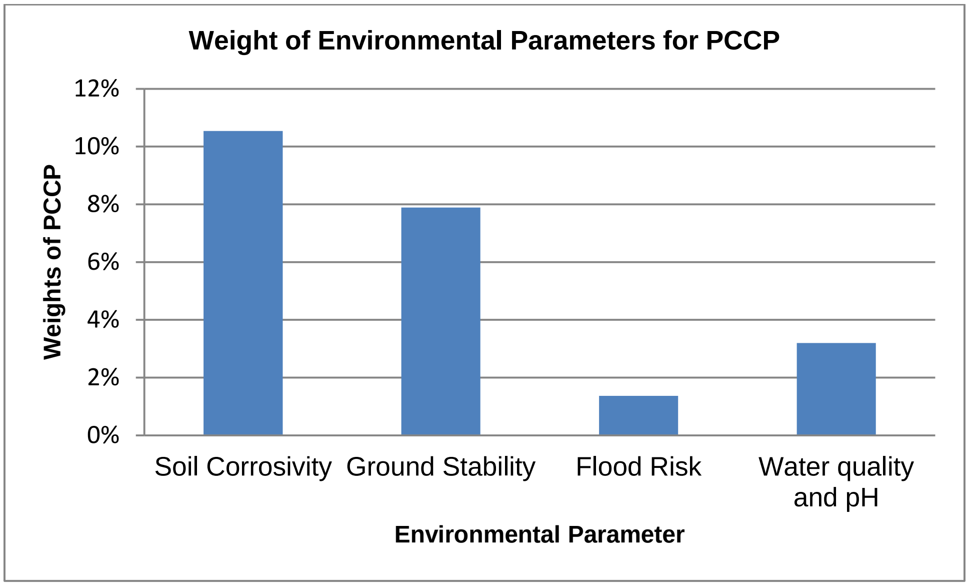


Figure 4.10 Weights for Environmental Parameters for PCCP

- According to the survey results of all the parameters corrosion is the leading cause for steel pipe failure. In case of PCCP pipes wire breaks was found to be the most important factor to be monitored.
- The final outcome of each of the pipeline monitoring technique against the risk factors for steel is depicted in *Figure 4.11*. Magnetic Flux Leakage followed by Brillouin Optical Time Domain Sensors is found to be the most pipeline inspection and monitoring technique respectively.
- Magnetic Flux leakage is a very suitable inspection technique and gives information about the current condition of the pipeline.
- Brillouin Optical Time Domain Sensors provides the real-time data and is suitable for on-pipe continuous monitoring.
- It was found that both Remote Field Eddy Current technique and Acoustic Emission Monitoring based using Fiber Optics are equally suitable for the inspection and monitoring of the structural integrity of PCCP. *Figure 4.12* shows the results for the analysis conducted for PCCP.
- Remote Eddy Field Current based wire break recognition techniques is most suitable for PCCP pipes to detect the existing number of wire breaks in a pipe that is in service.
- Fiber Optic Acoustic Emission Monitoring Sensors are most suitable for realtime wire break detection in PCCP pipes.

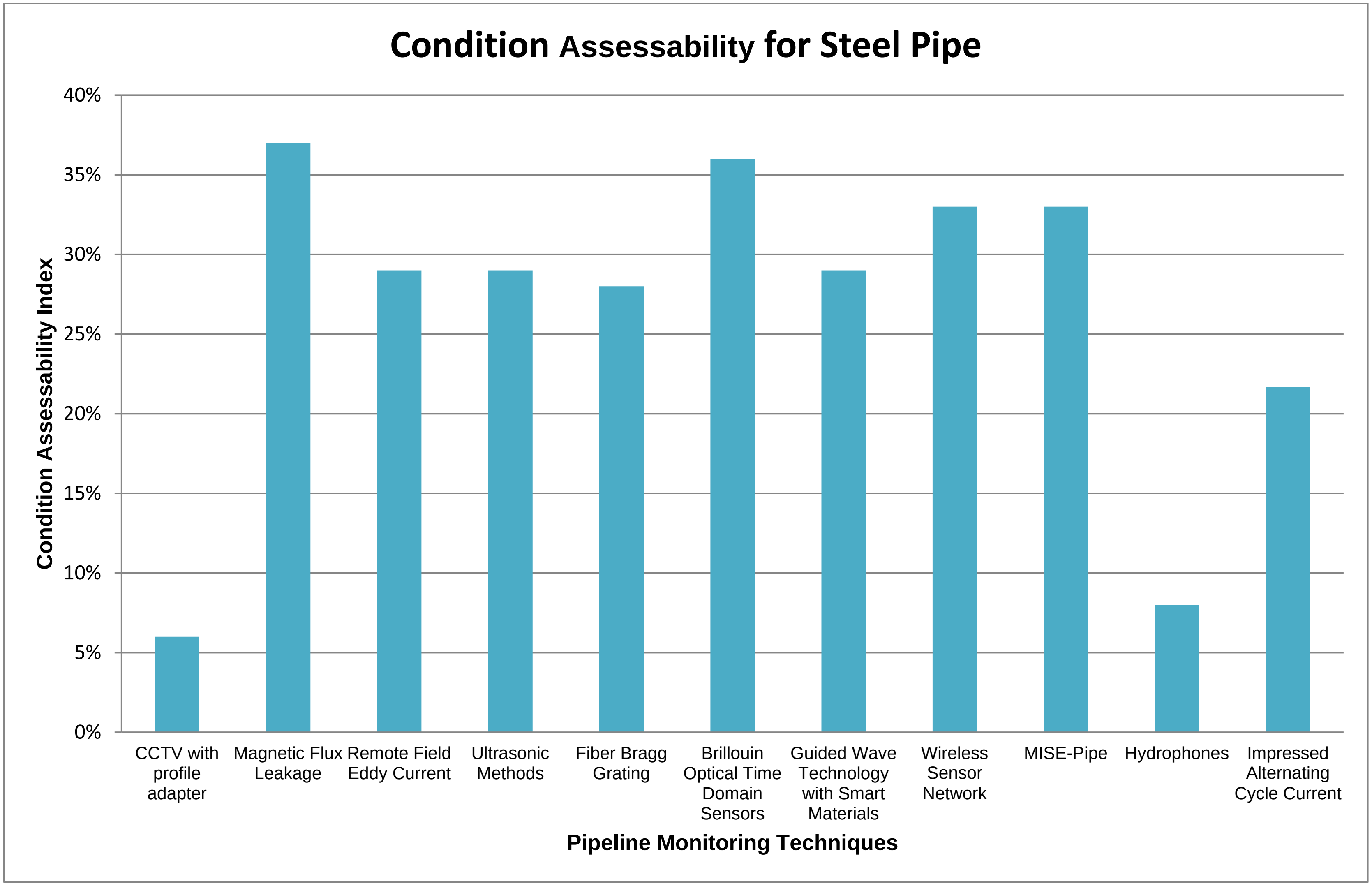


Figure 4.11 Condition Assessability for Steel Pipe

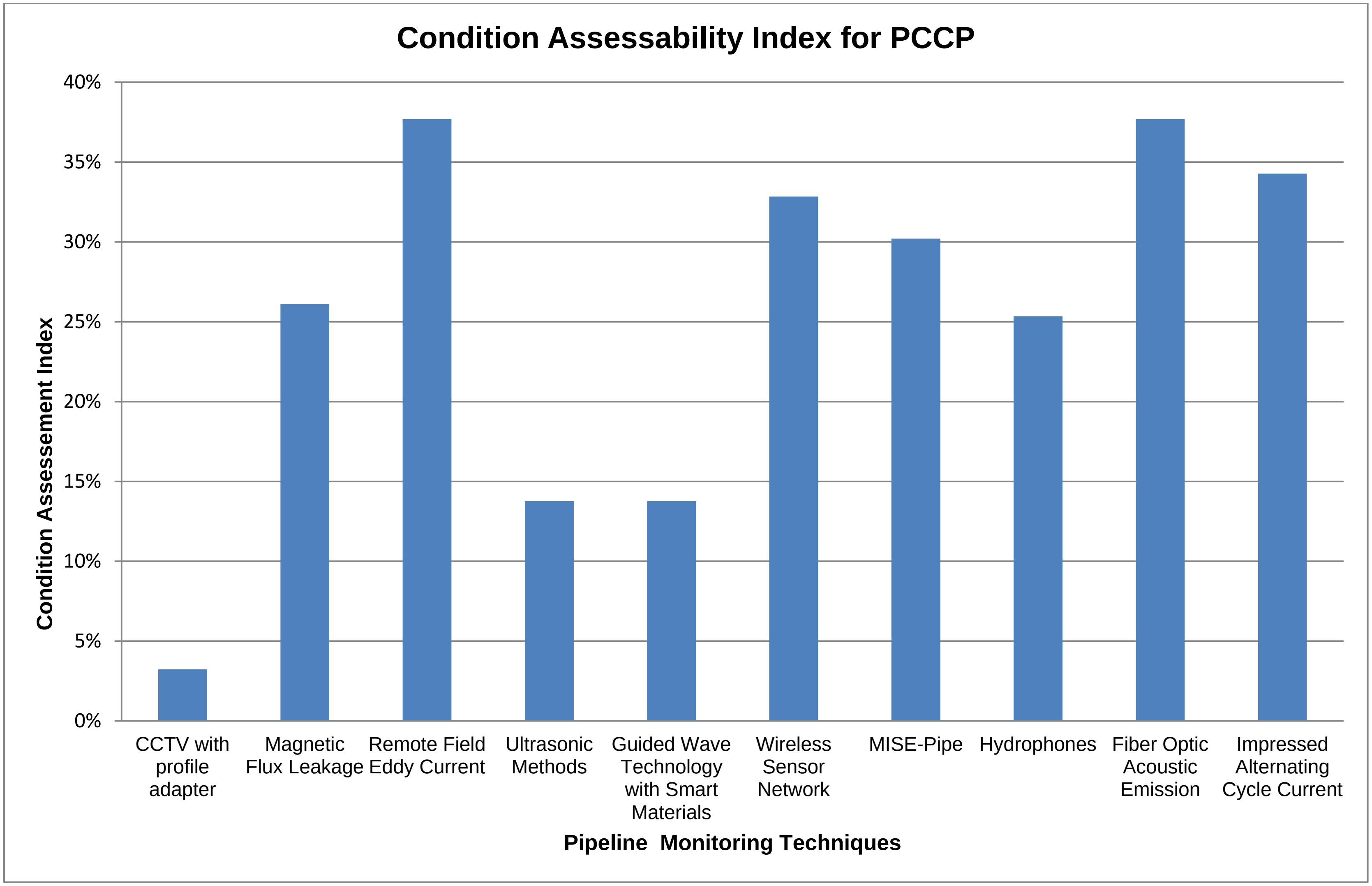


Figure 4.12 Condition Assessability Index for PCCP

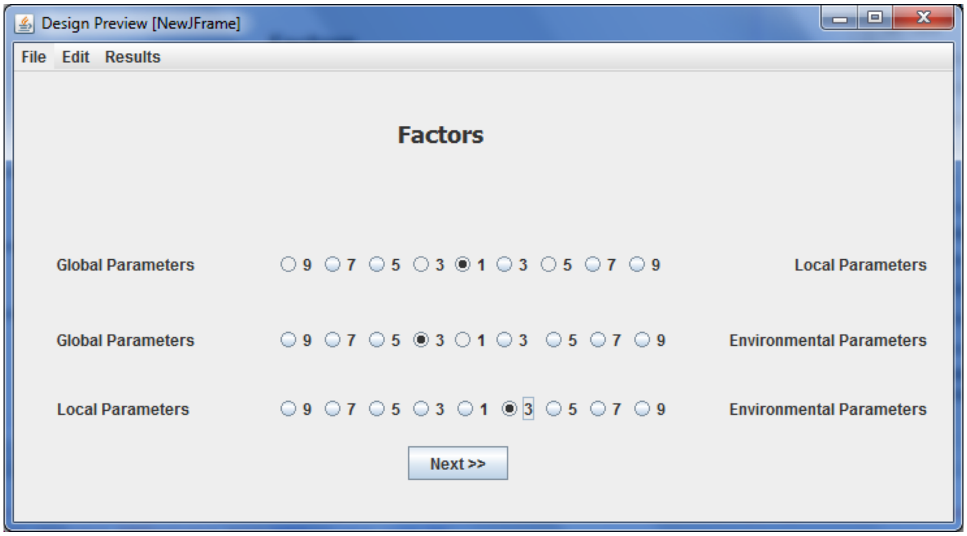
- *Table 4.3* shows the results from the case study conducted for IPL Project. Depending on the data available at the conceptual design and preliminary design stage, the most suitable monitoring technique are Fiber Bragg Grating Sensors and Brillouin Optical Time Domain Sensors. MISE Pipe technique can be used in locations with highly corrosive soil.

Table 4.3 IPL Project Case Study Results

Critical Areas	Length (ft)	Parameter to monitor	Suitable Technique (Steel)	Condition Assessability Index (Steel)	Suitable Technique (PCCP)	Condition Assessability Index (PCCP)
Major Roads	5068	External loading, strain/wire break	FBG Sensors, BOTDA Sensors	8%	RFI, Hydophones, AEM, IACC	21%
Railroads	1098	External loading, strain/wire break	FBG Sensors, BOTDA Sensors	8%	RFI, Hydophones, AEM, IACC	21%
River Crossings	353	Flood Risk, External loading, strain/wire break	FBG , BOTDA Sensors	10%	RFI, Hydophones, AEM, IACC	21%
Deep Tunnels	8,480	External loading, strain/wire break	FBG Sensors, BOTDA Sensors	8%	RFI, Hydophones, AEM, IACC	21%
Urban Areas	28,890	External loading, 3rd party intrusion, strain/wire break	FBG Sensors, BOTDA Sensors	15%	RFI, Hydophones, AEM, IACC	26%
Highly corrosive soils	Not available	Soil Corrosivity	MISE Pipe	11%	MISE Pipe	11%

4.3 Decision Support System Software Prototype

Prototype software for the decision support system was developed to provide a tool for quantifying the impact of the parameters critical to the structural integrity of the pipe. *Figure 4.13* through *Figure 4.15* show the user input screen for the software. This enables the user to rank the parameters according to their significance to the performance of the pipe. To facilitate data entry and reporting, a set of user-interactive screens was developed as shown in the following case example. *Figure 4.16* shows the result screen showing the overall priority from the AHP analysis conducted based on the user input. This screen also provides the recommendation on the type of pipe inspection and monitoring technique to employ based on the ranking of the parameters. Refer to Appendix E for User Manual for the Decision support System user interface.

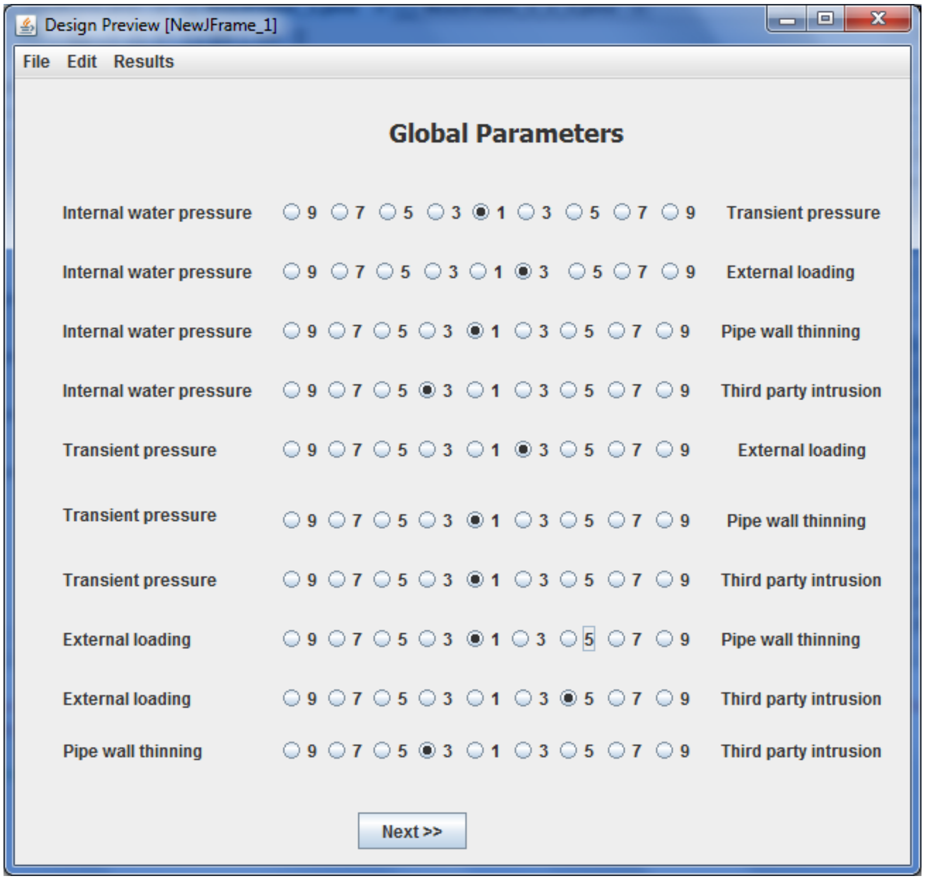


Global Parameters ○ 9 ○ 7 ○ 5 ○ 3 ● 1 ○ 3 ○ 5 ○ 7 ○ 9 Local Parameters

Global Parameters ○ 9 ○ 7 ○ 5 ● 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Environmental Parameters

Local Parameters ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ● 3 ○ 5 ○ 7 ○ 9 Environmental Parameters

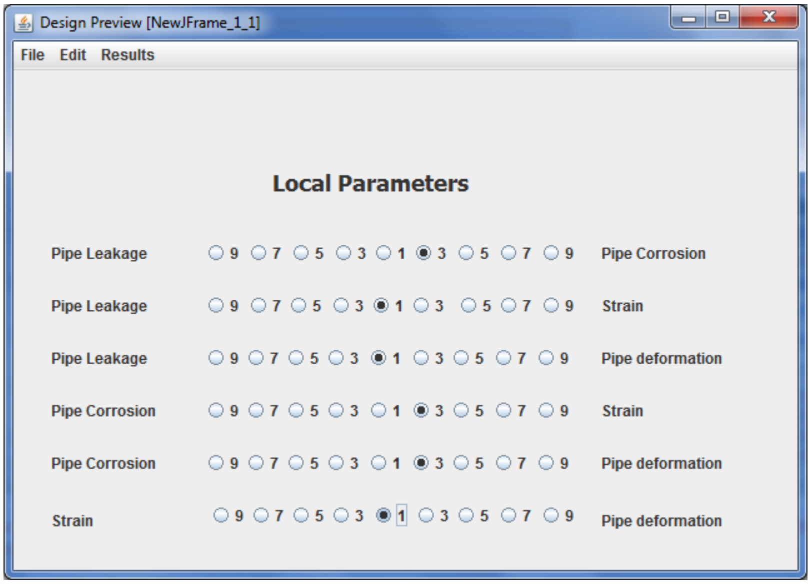
Figure 4.12 Comparative Analysis Input Screen for Factors



Global Parameters

Internal water pressure	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Transient pressure
Internal water pressure	○ 9	○ 7	○ 5	○ 3	○ 1	● 3	○ 5	○ 7	○ 9	External loading
Internal water pressure	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Pipe wall thinning
Internal water pressure	○ 9	○ 7	○ 5	● 3	○ 1	○ 3	○ 5	○ 7	○ 9	Third party intrusion
Transient pressure	○ 9	○ 7	○ 5	○ 3	○ 1	● 3	○ 5	○ 7	○ 9	External loading
Transient pressure	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Pipe wall thinning
Transient pressure	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Third party intrusion
External loading	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Pipe wall thinning
External loading	○ 9	○ 7	○ 5	○ 3	○ 1	○ 3	● 5	○ 7	○ 9	Third party intrusion
Pipe wall thinning	○ 9	○ 7	○ 5	● 3	○ 1	○ 3	○ 5	○ 7	○ 9	Third party intrusion

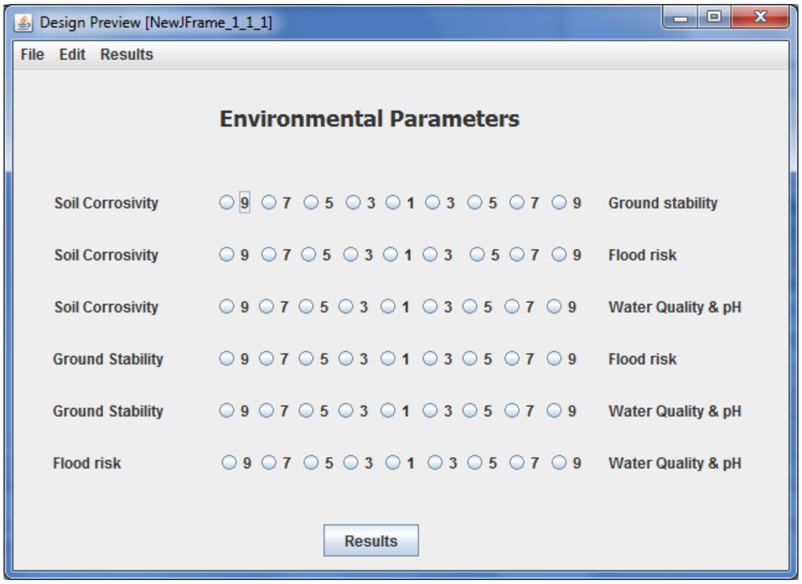
Figure 4.13 Comparative Analysis Input Screen for Global Parameters



Local Parameters

Pipe Leakage	○ 9	○ 7	○ 5	○ 3	○ 1	● 3	○ 5	○ 7	○ 9	Pipe Corrosion
Pipe Leakage	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Strain
Pipe Leakage	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Pipe deformation
Pipe Corrosion	○ 9	○ 7	○ 5	○ 3	○ 1	● 3	○ 5	○ 7	○ 9	Strain
Pipe Corrosion	○ 9	○ 7	○ 5	○ 3	○ 1	● 3	○ 5	○ 7	○ 9	Pipe deformation
Strain	○ 9	○ 7	○ 5	○ 3	● 1	○ 3	○ 5	○ 7	○ 9	Pipe deformation

Figure 4.14 Comparative Analysis Input Screen for Local Parameters



Environmental Parameters

Soil Corrosivity ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Ground stability

Soil Corrosivity ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Flood risk

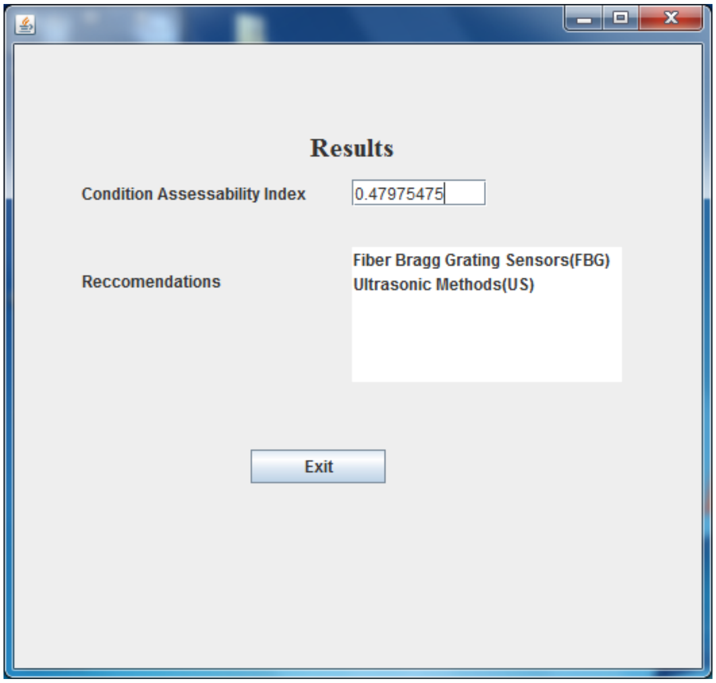
Soil Corrosivity ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Water Quality & pH

Ground Stability ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Flood risk

Ground Stability ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Water Quality & pH

Flood risk ○ 9 ○ 7 ○ 5 ○ 3 ○ 1 ○ 3 ○ 5 ○ 7 ○ 9 Water Quality & pH

Figure 4.15 Comparative Analysis Input Screen for Environmental Parameters



Results

Condition Assessability Index: 0.47975475

Reccomendations:
Fiber Bragg Grating Sensors(FBG)
Ultrasonic Methods(US)

Figure 4.16 Pipe Parameter Analysis Results and Recommendations

4.4 Chapter Summary

A model to calculate the condition assessability index based on the ability of state-of-the-art technology to measure pipe failure indicators is presented in this chapter. The model is based on the analytical hierarchal structure and was developed based on priority based parameters. Thirteen parameters grouped into groups of three were considered in the development of the model. The developed model evaluated the comparative analysis results from the survey conducted and provided the ranking for parameters. Based on this ranking the condition assessability index for the pipeline monitoring techniques was calculated. The developed model implemented in prototype software, which provides a user interface screen to facilitate the use of the model.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter presents the conclusions drawn from the results and findings obtained in Chapter 4. It also includes the recommendations that can be incorporated into further study for the same subject.

5.1 Conclusions

The conclusions for this research can be summarized as following:

- No single technique can satisfy all of the requirements for pipeline structural monitoring and different combinations of techniques will be appropriate in different circumstances.
- In order to identify the suitable inspection and monitoring technique to meet the particular pipe characteristics and failure modes, the methodology and tables developed within this study can be utilized.
- Selection of monitoring technology for pipelines depends on the pipe material, pipe diameter, performance, failure history, environmental data, and strategic importance.
- Condition assessability index will help the utility agencies to make an informed decision while developing an asset management plan for their underground infrastructure.
- Corrosion related failures are found to be most critical for steel pipes. In pressurized steel pipes corrosion manifests itself as cracks and leakages. Deterioration of Pre-stressed Concrete Cylinder Pipe involves the reduction of corrosion protection offered to the steel wires from the cement mortar followed by the corrosion and failure of pre-stressed steel wires.
- Fiber optic sensors in particular are being viewed as a good candidate for a range of sensing tasks. The reason for the popularity of these sensors is mainly due to their real-time, continuous, long range monitoring capability.

5.2 Recommendations for Future Research

The recommendations for future study can be summarized as following:

- Include various types of pipe materials used in the water and wastewater industry.
- Conduct survey including more number of participants.
- Include cost benefit analysis to study the advantage of including monitoring techniques in a pipeline asset management plan.
- Include analysis of failure history of large diameter water mains to rank pre-failure indicators.
- Identify gap between technologies by considering various high-risk distress indicators with no suitable monitoring techniques available.

APPENDIX A

PHOTOGRAPHS OF PIPELINE MONITORING TECHNIQUES

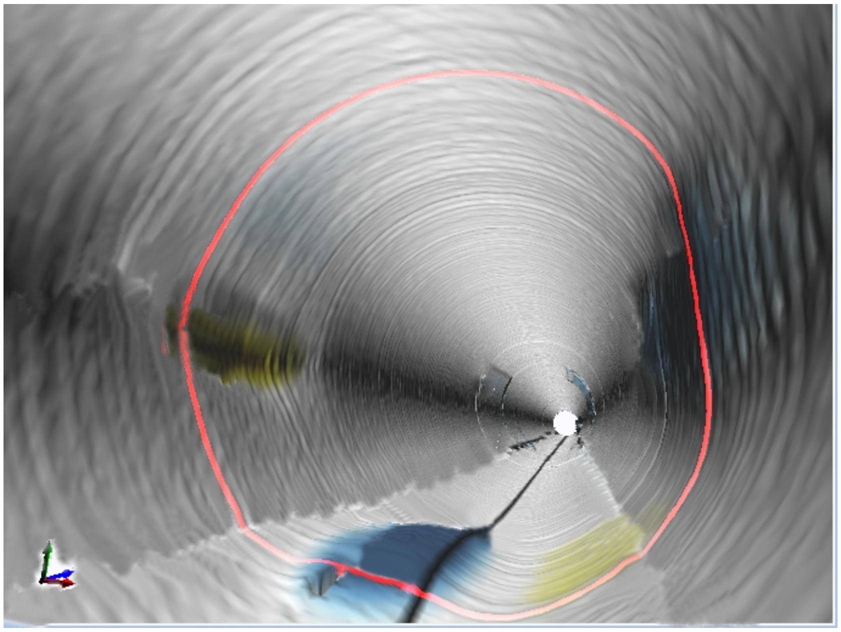


Figure A.1 CCTV camera with laser profile adapter
Source: www.maverickinspection.com

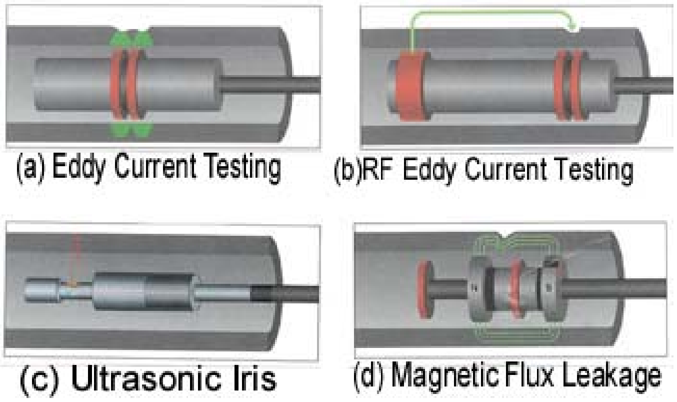


Figure A.2 Electromagnetic and Ultrasonic Inspection Techniques
Source: www.nde.com

Figure A.3 Magnetic Flux Leakage Pig
Source: www.aquaenvironmental.com

Figure A.4 MFL/Ultrasonic Pigs
Source: www.ppsa-online.com

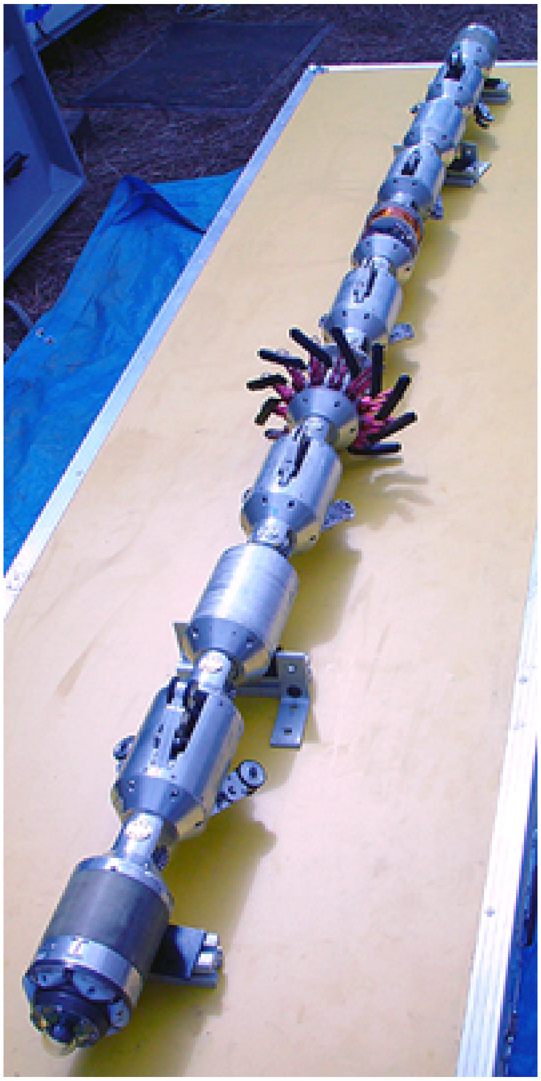


Figure A.5 RFEC/TC Pig
Source: www.netl.doe.gov

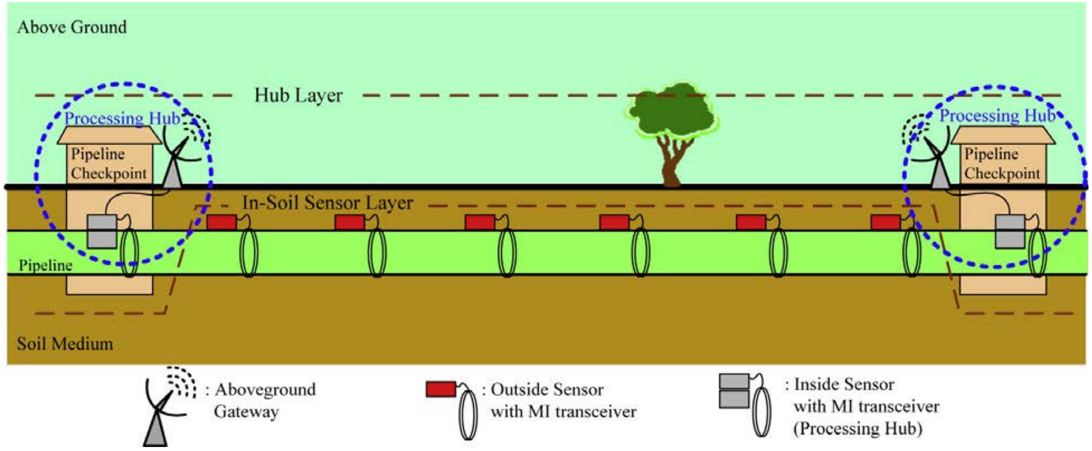


Figure A.6 MISE Pipe
Source: (Sun, 2010)

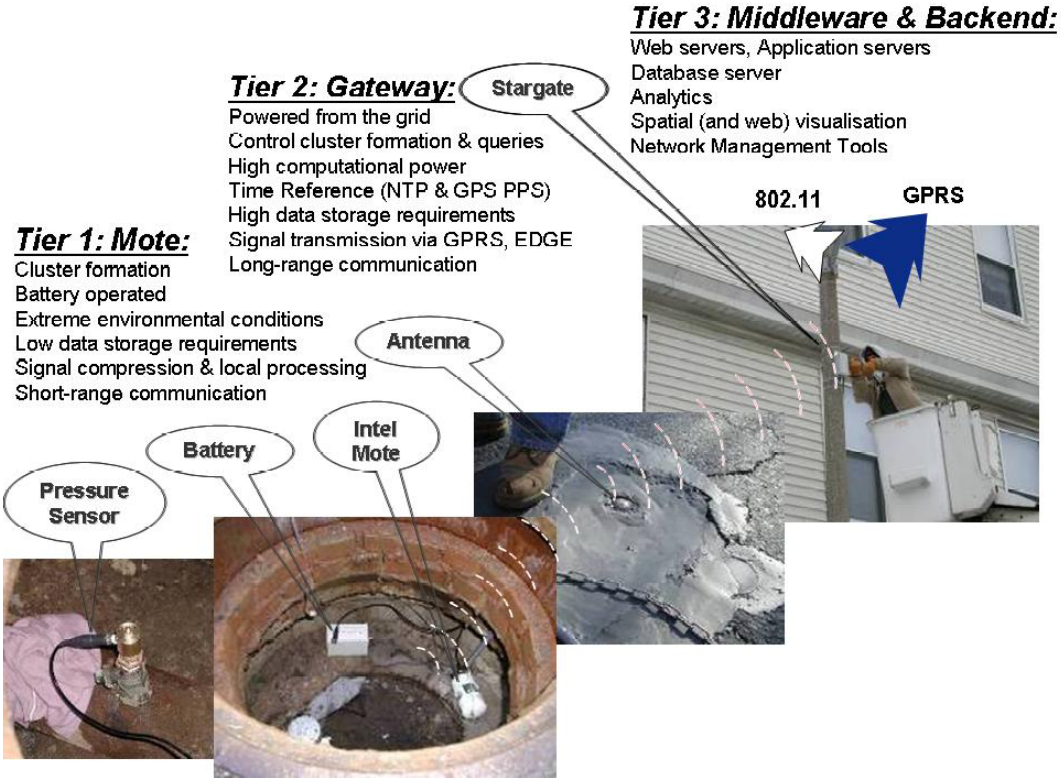


Figure A.7 Wireless Sensor Network
Source: Stoianov et al, 2007

APPENDIX B

PAIR-WISE COMPARISON SURVEY SAMPLE QUESTIONNAIRE

Date	
Name:	
Title:	
Name of Company:	

Intensity of Importance	Definition	Explanation
1	**Equal Importance**	Two parameters have equal importance
3	**Moderate Importance**	Experience and judgment **slightly** favors one parameter over other
5	**Strong Importance**	Experience and judgment **strongly** favors one parameter over other
7	**Very Strong Importance**	One parameter is favored very strongly over another; its dominance demonstrated in practice
9	**Extreme Importance**	One parameter is favored over the other in the highest form of affirmation
2,4,6,8	**Intermediate Values**	Where compromise is required

Global Parameters: Indicates the general pipeline condition: Internal/transient water pressure, external loading, third party intrusion, etc.

Local Parameters: Indication of localized problems,: Leaks, local strain, pipe deformation, corrosion.

Environmental Parameters: Soil corrosivity, ground stability, water quality and pH, flood risk potential.

Parameter A	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Parameter B**
Global Parameter	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Local Parameter**
Global Parameter	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Environmental Parameter**
Local Parameter	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Environmental Parameter**

Global Parameters

Parameter A	9	7	5	3	1	3	5	7	9	**Parameter B**
Internal water pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Transient Pressure**
Internal water pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**External load on pipe**
Internal water pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Wall thickness reduction**
Internal water pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**3rd party intrusion**
Transient Pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**External load on pipe**
Transient Pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Wall thickness reduction**
Transient Pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	**3rd party intrusion**
External load on pipe	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Wall thickness reduction**
External load on pipe	☐	☐	☐	☐	☐	☐	☐	☐	☐	**3rd party intrusion**
Wall Thickness reduction	☐	☐	☐	☐	☐	☐	☐	☐	☐	**3rd party intrusion**

Local Monitoring Parameters

Parameter A	9	7	5	3	1	3	5	7	9	**Parameter B**
Pipe Leak	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Pipe Corrosion**
Pipe Leak	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Local Strain (wire break in case of PCCP)**
Pipe Leak	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Pipe deformation**

Pipe Corrosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Local Strain (wire break in case of PCCP)**
Pipe Corrosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Pipe deformation**
Local Strain (wire break in case of PCCP)	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Pipe deformation**

Environmental Parameters

Parameter A	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Parameter B**
Soil Corrosivity	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Water quality and pH**
Soil Corrosivity	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Ground Stability**
Soil Corrosivity	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Flood Risk Potential**
Water quality and pH	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Ground Stability**
Water quality and pH	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Flood Risk Potential**
Ground Stability	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Flood Risk Potential**

APPENDIX C

PIPELINE MONITORING TECHNIQUE - USER RESPONSES

Questionnaire for Real-time Monitoring Technique Users

Date	
Name:	
Title:	
Name of Company/Agency:	

1. What type of monitoring techniques do you utilize for the periodic monitoring and maintenance of your pipelines?

Steel

PCCP

2. Which all parameters do you measure using these techniques?

Technique	Parameters Measured

3. What are the advantages and limitations that you observed for each of these methods?

Technique	Advantages	Limitations

4. Who are the vendors for these techniques?

Technique	Vendor

5. What kind of installation was performed for the on-pipe techniques? Are they place inside or outside the pipe?

6. What kind of Data Gathering techniques do you use?

7. How far apart are the data acquisitions systems placed on site?

8. How often do you receive data from the realtime monitoring techniques employed?

9. How do you receive the data? Eg: Collect on site, remote access, emails?

10. Do you feed this data into any other interface to facilitate the monitoring? Eg: SCADA, GIS

11. In case of line breaks (cable connecting the sensor to the data acquisition system) do you have alternative methods to prevent losing of data?

12. Do you have these techniques installed for the entire length of the pipeline or for certain segments?

13. If only installed for certain segments based on what conditions prioritize the particular segments?

14. How long have you been using these techniques? How often did you have to repair/replace them?

Technique	Period of Maintenance

15. What kind of maintenance issues have you faced with these techniques?

Technique	Maintenance Issues

APPENDIX D

IPL PROJECT SEGMENT TERRAIN DETAILS

Table D.1: Terrain Details for IPL Project (IPL Project Conceptual Design Report)

Segment 19				
Mode of Installation	**Major Classification**	**Length (LF)**	**Detailed Classification**	**Length (LF)**
Open Cut	Crossings	2,441	Minor Road	677
			Water Body	1,764
	Rural	213,869	Pasture	117,970
			Cropland	-
			Wooded	95,899
	Urban	2,747	Light Urban	2,747
			Medium Urban	-
			Heavy Urban	-
Tunnel	Crossing Tunnel	1,337	Railroad	142
			River	-
			Major Road	1195
	Deep Tunnel	-	Deep Tunnel	-
Total Length-Segment 19				**220,394**
Segment 17				
Mode of Installation	**Major Classification**	**Length (LF)**	**Detailed Classification**	**Length (LF)**
Open Cut	Crossings	215	Minor Road	131
			Water Body	84
	Rural	25,591	Pasture	18,419
			Cropland	-
			Wooded	7,172
	Urban	-	Light Urban	-
			Medium Urban	-
			Heavy Urban	-
Tunnel	Crossing Tunnel	353	Railroad	-
			River	353
			Major Road	-
	Deep Tunnel	-	Deep Tunnel	-
Total Length-Segment 17				**26,159**

Segment 15				
Mode of Installation	**Major Classification**	**Length (LF)**	**Detailed Classification**	**Length (LF)**
Open Cut	Crossings	1,831	Minor Road	1,115
			Water Body	698
	Rural	310,388	Pasture	166,885
			Cropland	85,975
			Wooded	57,528
	Urban	14,249	Light Urban	14,249
			Medium Urban	0
			Heavy Urban	0
Tunnel	Crossing Tunnel	2,938	Railroad	767
			River	0
			Major Road	2171
	Deep Tunnel	-	Deep Tunnel	
Total Length-Segment 15				**329,388**

Segment 9,11				
Mode of Installation	**Major Classification**	**Length (LF)**	**Detailed Classification**	**Length (LF)**
Open Cut	Crossings	1,137	Minor Road	924
			Water Body	213
	Rural	93,032	Pasture	56,708
			Cropland	14,139
			Wooded	22,185
	Urban	10,412	Light Urban	10,197
			Medium Urban	215
			Heavy Urban	0
Tunnel	Crossing Tunnel	1,070	Railroad	189
			River	0
			Major Road	881
	Deep Tunnel	8,480	Deep Tunnel	8,480
Total Length-Segment 15				**114,131**

Segment 18

Mode of Installation	Major Classification	Length (LF)	Detailed Classification	Length (LF)
Open Cut	Crossings	29	Minor Road	29
			Water Body	-
	Rural	8,370	Pasture	-
			Cropland	7,557
			Wooded	813
	Urban	-	Light Urban	-
			Medium Urban	-
			Heavy Urban	-
Tunnel	Crossing Tunnel	118	Railroad	-
			River	-
			Major Road	118
	Deep Tunnel	-	Hydraulic Advantage	-
Total Length-Segment 9,11				**8,517**

Segment 16

Mode of Installation	Major Classification	Length (LF)	Detailed Classification	Length (LF)
Open Cut	Crossings	2,441	Minor Road	400
			Water Body	152
	Rural	213,869	Pasture	36,358
			Cropland	5,803
			Wooded	14,556
	Urban	2,747	Light Urban	0
			Medium Urban	0
			Heavy Urban	0
Tunnel	Crossing Tunnel	1,337	Railroad	120
			River	0
			Major Road	369
	Deep Tunnel	-	Deep Tunnel	0
Total Length-Segment 16				**57,768**

Segment 12

Mode of Installation	**Major Classification**	**Length (LF)**	**Detailed Classification**	**Length (LF)**
Open Cut	Crossings	27	Minor Road	27
			Water Body	0
	Rural	6,759	Pasture	172
			Cropland	5,989
			Wooded	598
	Urban	0	Light Urban	0
			Medium Urban	0
			Heavy Urban	0
Tunnel	Crossing Tunnel	334	Railroad	0
			River	0
			Major Road	334
	Deep Tunnel	0	Deep Tunnel	0
Total Length-Segment 12				**7,120**

Segment 10

Mode of Installation	Major Classification	Length (LF)	Detailed Classification	Length (LF)
Open Cut	Crossings	2,441	Minor Road	178
			Water Body	0
	Rural	213,869	Pasture	8,922
			Cropland	0
			Wooded	4,183
	Urban	2,747	Light Urban	1,482
			Medium Urban	0
			Heavy Urban	0
Tunnel	Crossing Tunnel	1,337	Railroad	0
			River	0
			Major Road	0
	Deep Tunnel	-	Deep Tunnel	0
Total Length-Segment 10				**14,765**

APPENDIX E

USER MANUAL FOR DECISION SUPPORT SYSTEM

Getting Started

This Decision Support System opens with a start page with a button to get started with the Decision Support System. The system is based on a hierarchical model. The user has to do a pairwise comparison of the given parameters. The following screens put forward a set of parameters related to pipe failure detection.

Using the Decision Support System

The user has to rate the given scenarios based on the criticality of each distress indicator and the need to monitor these parameters to predict the pipe failure.

Table F.1 Saaty's1-9 Scale of relative importance for pair-wise comparison

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the object
3	Moderate importance	Slightly favors one over another
5	Essential or strong importance	Strongly favors one over another
7	Demonstrated importance	Dominance of the demonstrated in practice
9	Extreme importance	Evidence favoring one over another of highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

Navigating the Decision support system

Screen 1: Comparison of factors: In the first screen the user has to compare between global parameters, local parameters and environmental parameters.

Screen 2: Comparison factors: In this screen the user has to compare five global parameters which include internal water pressure, transient pressure, external loading, pipe wall thinning, and third party intrusion.

Screen 3: Comparison factors: In this screen the user has to compare four local parameters which include pipe leak, corrosion, local strain, and deformation.

Screen 4: Comparison factors: In this screen the user has to compare four environmental parameters which include soil corrosivity, water quality and pH, ground stability, and flood risk.

Screen 5: Results: The result screen shows the result of the AHP analysis performed based on the inputs from screens 1 through 4. Overall priority value shows the highest condition assessability value for the chosen inspection and monitoring technique. Recommendations give the list of techniques that are suitable to be used for monitoring parameters based on the user input.

Definitions

Global parameters: Global parameters give indication of general pipeline conditions which when combined with data from other monitoring and condition assessment techniques gives a complete picture of the integrity of the pipeline.

Local Parameters: Local parameters give indication of the localized problems which could lead to potential failure. This data when combined with all the other data would assist in predicting the susceptible segments in the pipeline.

Environmental Parameters: Deterioration of pipeline wall structure when reaches a point where it can no longer endure the internal pressure or external load leads to local failures.

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BIOGRAPHICAL INFORMATION

Moksha Kizhakke Covilakam graduated in May 2005 with a Bachelors Degree in Civil Engineering from the Kerala University, India. She has continued to maintain a strong academic standing while pursuing a Masters in the area of Construction Management and Engineering at the University of Texas at Arlington. Ms. Covilakam has been under employment of the Center for Underground Infrastructure Research and Education (CUIRE) at the University of Texas at Arlington as a Graduate Research Assistant from June 2010 to May 2011. She is currently working as an Engineering Intern with Parsons Corporation. She has been the recipient of Civil Engineering Department Graduate Scholarship for Fall 2011 semester. She has served as the President of UT Arlington student chapter of Texas Society of Professional Engineers (TSPE).