CHAPTER (2)

LITERATURE REVIEW

2.1 General:

One of the greatest challenges facing municipal engineers is the condition rating of buried infrastructure assets, particularly water mains. This is because water mains are typically underground, operated under pressure, and usually inaccessible. Condition rating is a mandatory process to establish and employ management strategies for any asset. To assess the condition of water mains, current research considers physical, environmental, and operational factors and their effect on different types of mains (i.e., cast iron, ductile iron, and asbestos).

The condition of water mains can be determined by two methods: (1) applying direct inspection methods for all the pipes in the network, which is often too expensive, or (2) using one of the developed condition rating models, which is considered an effective and inexpensive alternative.

2.2 type and failure of pipes:

A water delivery system can be divided into two main categories: transmission and distribution lines. Transmission lines are the pipes that transfer water from the main source to the storage system (i.e., water tanks). They are considered as the most expensive part in the system because they have the largest diameter. Distribution lines are the pipes that carry water out from the storage system to the domestic users (i.e., residential buildings or industrial factories). Water mains consist of different types of pipes with different materials. They not only vary from country to country, but from city to city as well (Rajani and Kleiner 2004). The major types of pipes that are commonly used in a water system are classified according to their material, as shown in Fig. 1.

Pipes will deteriorate and fail overtime, but the rate of failure in pipes varies according to the pipe's material and exposure to different environmental and operational conditions (Makar and Kleiner 2000). Deterioration of pipes will affect the structural condition and hydraulic capacity of a water main, which decreases the system performance. Rajani and Kleiner (2004) stated that deterioration of pipes generally could be classified into two categories: structural and internal deterioration. Structural deterioration affects the structural resiliency of pipes and their ability to resist various applied stresses. However,
internal deterioration of pipes affects hydraulic capacity and water quality, and reduces the structural resiliency of the pipe.

Makar and Kleiner (2000) stated that corrosion is the main reason for metallic pipe failure. Metallic pipe deteriorate and corrode rapidly if they are laid in aggressive soil in which they might fail within a few years. Therefore, if metallic pipes are laid in aggressive soil, they should be wrapped in plastic sheets to isolate the metal from the soil, and hence minimize the rate of pipe deterioration (Saint-Gobain 2002).

Similarly, corrosion is the main reason for failure in prestressed concrete pipes [concrete pressure pipes/prestressed concrete cylinder pipes (CPP/PCCP)]. When enough of the prestressed bars or wires are corroded and broken in a section of the pipe, the concrete in that section will not transmit pressure. As a result, the pipe will rupture due to internal pressure (Makar and Kleiner 2000). The CPP and PCCP are also weakened when they are laid in soil with low pH values resulting in lowering the pH value of the cement mortar to a point where corrosion of the prestressing or reinforcing wires occurs (Rajani and Kleiner 2004).

Asbestos cement (AC) pipes can also be weakened and degraded when they are used to transfer aggressive water such as low pH and low alkalinity waters (Rajani and Kleiner 2001). The degradation of the pipe will release asbestos fibers, which are harmful to health, and mix them with the water carried through the water distribution system. In order to prevent this type of damage, the pipe should be lined with epoxy resin or cement mortar (Department of the Environment 1988).

Polyvinyl chloride [polyvinyl chloride pipes/unplasticized polyvinyl chloride (PVC/UPVC)] pipes have high resistance to deterioration and corrosion, and can be used in very corrosive environments, but they are likely to be affected by deterioration if they are exposed to weather, chemical attack, or mechanical degradation from improper installation methods (Blaga 1973). The chemical attack resistance for PVC pipes usually decreases with increase in concentration of a specific chemical. For example, organic chemicals such as solvents and gasoline will weaken PVC or UPVC pipes, resulting in failure of the pipe by expansion and rupture. Similarly, high density polyethylene (HDPE) pipes deteriorate and fail due to joint imperfections, material degradation, and improper pipe installation. In addition, organic chemicals can pass through the walls of a HDPE pipe (Blaga 1981, 1982; Best Practices 2003b).

Based on the above discussion, deterioration of water mains varies due to certain surrounding and operational conditions. In order to decrease deterioration and failure of pipes, municipal engineers have to make comprehensive studies on physical, envi-
Environmental, and operational conditions. The soil should also be tested before selecting pipe material. In other words, the pipe material has to match the soil conditions. They have to decide which type of pipe would be feasible to use under a proposed condition through sensitivity analysis and life cycle cost.

**Figure 2-1: Type of Water Pipes (Al-Barqawi 2006)**

### 2.3 Factors that Contribute to Water Main Deterioration:

Different factors affect the breakage and deterioration rate of water mains. Kleiner and Rajani (2001) reported that these factors include operational, environmental, and physical characteristics. They also reported that the breakage rate of buried pipes could be subjective due to different time-dependent factors as well as climatic conditions and soil shrinkage behavior. Rajani and Kleiner (2001) reported that structural capacity is subject to external and internal loads considering soil pressure, traffic loading, frost loads, operational pressure, and third party interference. Kleiner and Rajani (2002) classified water main deterioration factors into three types.
1. Static factors. They are static over time due to properties of the pipe and installation practice. They include pipe material, diameter, wall thickness, soil (backfill) characteristics, and installation practices.

2. Dynamic factors (related to pipe surroundings and environment). They include age, soil properties, temperature of soil and water, moisture, electrical resistivity, bedding condition, and dynamic loadings.

3. Operational factors. They include replacement rate, protection methods such as cathodic protection, and water pressure.

Best Practices (2003b) classified the factors that contribute to water main deterioration into three groups, as shown in Table 1.

1. Physical factors: pipe material, wall thickness, pipe age, diameter, type of joints, thrust restraint, pipe lining and coating, dissimilar metals, pipe vintage, and manufacturing processes.

2. Environmental factors: soil type, soil moisture, groundwater presence, climate, pipe location in the road, trench backfill materials, pipe bedding, underground disturbances, stray electrical currents, seismic activity, and installation practices.

3. Operational factors: internal water pressure, leakage, water quality, flow velocity, backflow potential and operational and maintenance practices.

It should be noted that the deterioration processes of water systems are neither uniform nor identical. They vary based on different uncertain factors, which can cause variations in the condition level, and hence they vary from one water distribution network to another.
**Table 1: Contributing Factors to Water System Deterioration (Adapted from Best Practices, 2003b)**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Pipe material</td>
<td>Pipes made from different materials fail in different ways</td>
</tr>
<tr>
<td>Pipe wall thickness</td>
<td>Corrosion will penetrate thinner walled pipe more quickly</td>
</tr>
<tr>
<td>Pipe age</td>
<td>Effects of pipe degradation become more apparent over time</td>
</tr>
<tr>
<td>Pipe vintage</td>
<td>Pipes made at a particular time and place may be more vulnerable to failure</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>Small diameter pipes are more susceptible to beam failure</td>
</tr>
<tr>
<td>Type of joints</td>
<td>Some types of joints have experienced premature failure (e.g., leadite joints).</td>
</tr>
<tr>
<td>Thrust restraint</td>
<td>Inadequate restraint can increase longitudinal stresses</td>
</tr>
<tr>
<td>Pipe lining and coating</td>
<td>Lined and coated pipes are less susceptible to corrosion</td>
</tr>
<tr>
<td>Dissimilar metals</td>
<td>Dissimilar metals are susceptible to galvanic corrosion</td>
</tr>
<tr>
<td>Pipe installation</td>
<td>Poor installation practices can damage pipes, making them vulnerable to failure</td>
</tr>
<tr>
<td>Pipe manufacture</td>
<td>Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Improper bedding may result in premature pipe failure</td>
</tr>
<tr>
<td>Trench backfill</td>
<td>Some backfill materials are corrosive or frost susceptible</td>
</tr>
<tr>
<td>Soil type</td>
<td>Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Some groundwater is aggressive toward certain pipe materials</td>
</tr>
<tr>
<td>Climate</td>
<td>Climate influences frost penetration and soil moisture. Permafrost must be considered in the North.</td>
</tr>
<tr>
<td>Pipe location</td>
<td>Migration of road salt into soil can increase the rate of corrosion</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe</td>
</tr>
<tr>
<td>Stray electrical currents</td>
<td>Stray currents cause electrolytic corrosion</td>
</tr>
<tr>
<td>Seismic activity</td>
<td>Seismic activity can increase stresses on pipe and cause pressure surges</td>
</tr>
<tr>
<td><strong>Operational</strong></td>
<td></td>
</tr>
<tr>
<td>Internal water pressure, transient pressure</td>
<td>Changes to internal water pressure will change stresses acting on the pipe</td>
</tr>
<tr>
<td>Leakage</td>
<td>Leakage erodes pipe bedding and increases soil moisture in the pipe zone</td>
</tr>
<tr>
<td>Water quality</td>
<td>Some water is aggressive, promoting corrosion</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>Rate of internal corrosion is greater in unlined dead-ended mains</td>
</tr>
<tr>
<td>Backflow potential</td>
<td>Cross connections with systems that do not contain potable water can contaminate water distribution system</td>
</tr>
<tr>
<td>Operation and maintenance practices</td>
<td>Poor practices can compromise structural integrity and water quality</td>
</tr>
</tbody>
</table>
2.4 INSPECTION AND EVALUATION METHODS FOR EXISTING WATER MAINS:

Best Practices (2003b) reported that inspecting the condition of water mains passes through two phases: (i) an initial assessment of structural condition, hydraulic capacity, leakage, and water quality based on the collected data and (ii) a more comprehensive investigation of identifiable problems based on the results of the first phase. Furthermore, Makar et al. (2000) reported that there are two main methods to evaluate the condition of water system. First method, indirect indicators and statistical methods, which are based on the collected data that show pipe damage, such as water audit and hydrostatic leakage test. Hence, statistical models can be developed to assess the condition of water system elements. Second method, direct inspection and monitoring techniques, applies destructive and non-destructive evaluation techniques (DT and NDT) that detects problems in individual pipes or at a particular point along the pipe. It provides a variety of information related to pipe conditions.

2.4.1 Direct methods for pipe inspection:

2.4.1.1 Visual inspection:

a- Closed-circuit television (CCTV) inspection:

Closed-circuit television is a well-adopted technique for the inspection of the pipe’s inner surface. CCTV inspection is mainly applied to sewers and storm water pipes. For the inspection of water pipes, CCTV is commonly used for water main rehabilitation. A CCTV system comprises of a CCTV camera and lighting apparatus mounted on a carrier. A winch and pulley system moves the CCTV module through the pipe. Larger modules can use an umbilical cord system, which can supply power and communication to the control center and act as a retrieval device. The basic steps for a CCTV survey include:

- Introduce a carrier with the CCTV camera into the pipe via an access point.
- Operate the carrier to travel along the pipe and the camera captures and transmits the video to ground station (inspection truck).
- Transfer data from inspection truck to office computer.
- Do the survey in the office.
b- Laser scan:

Distance measurement by laser can be done using one of four principles, including triangulation, time-of-flight, pulse-type time-of-flight, and modulated beam systems. In a triangulation system, the detecting element measures the laser spot within its field of view. Usually, this type of laser measurement is used for distances around ten centimeters (a few inches).

Time of flight sensors derive range from the time it takes light to travel from the sensor to the target and back. This technology is typically used for relatively long distance measurements. For very long distances, a pulsed laser beam is used. A modulated beam system also uses the time duration for light to travel to the target and back; however, in this case, time is not measured directly. Instead, the strength of the laser is varied to produce a signal that changes over time. The time delay is indirectly discerned by comparing the signal from the laser with the delayed signal returning from the target. Modulated beam sensors are typically used in intermediate range applications.

To acquire pipe inner profile, a spinning apparatus is needed to control the laser beam. Such a laser range measurement does not require any special illumination and can be carried out in complete darkness. The speed of spinning, sampling rate, and carrier moving velocity determine the resolution and affect the accuracy of the scanning. The inspection is affected by the roughness as well as the color of the pipe surface.

Another method is based on structured light, which makes use of a ring of laser light projected onto the pipe inner surface. A detecting camera is used to capture the images of this projected ring. The laser device moves with the camera through the pipe. Analysis software extracts the shape of the laser ring from captured images and reconstructs a digital pipe profile. This profile can be easily unfolded or manipulated for review and analysis. The measurement for diameter, perimeter, and cross sectional area is accurate if both the camera and laser are properly set. However, ‘‘depth’’ information is missing.
A portable device, which is a combination of laser and stereo vision, has been demonstrated for fast creation of surface profile with high resolution. By tracking the laser beam (pattern) and positioning targets (marks on the surface to match images), separate images acquired by the two cameras are stitched together with the help of special software.

Currently available laser profiling systems are only used in de-watered pipes. To date there is no known report on underwater laser profiling for in-service water mains. The laser profiling is accurate, but still needs data processing to compensate for errors introduced during scanning. Report on performance study is not available. (adapted from Z. Liu, Y. Kleiner 2013)

2.4.1.2 Electromagnetic methods:

a- Magnetic flux leakage (MFL):

Z. Liu, Y. Kleiner (2013) stated that the magnetic flux leakage method uses large magnets to induce a saturated magnetic field around the wall of a ferrous pipe. If the pipe is in good condition, a homogeneous distribution of magnetic flux is obtained. Anomalies such as metal loss will alter the distribution of the magnetic flux. The damaged areas cannot support as much magnetic flux as undamaged areas, resulting in an increase of the flux field at the damaged areas. In other words, the damaged areas cause a change in magnetic reluctance in the closed magnetic circuit resulting in a change in the amount of flux leakage into the air. Such flux leakage is recorded by a magnetic sensor as shown in Fig. 2.3.

J.W. Wilson, M. Kaba, G.Y. Tian (2008) reported that the MFL test needs to be calibrated to interpret the acquired data for pipe wall thickness measurement. In order to discern defect’s depth in rolled steel water pipeline, a pulsed excitation for MFL was suggested in because more information is available from the response of a wider frequency band. However, the use of MFL in water industry is limited to cleaned, unlined pipes and also requires accessibility to the pipes’ exterior. The pulsed excitation for MFL has been developed to extract depth information of defects in rolled steel water pipeline.

![Fig.2. 3 the principle of magnetic flux leakage testing. (Adapted from Z. Liu, Y. Kleiner, 2013)](image-url)
**b- Remote field eddy current (RFEC):**

A remote field eddy current system consists of an exciting coil and one or more detectors. The exciting coil is driven by a low-frequency alternating current signal. The interaction region is divided into three zones as shown in Fig. 2.4:

- **Direct coupled zone:** magnetic field from the exciting coil interacts with the pipe wall to produce a concentrated field of eddy current.
- **Transition zone:** there is interaction between the magnet flux from the exciting coil and the flux induced by the eddy current.
- **Remote field zone:** this is the region in which direct coupling between the exciting coil and the receiver coil is negligible.

Two distinct coupling paths exist between the exciter and detector. The direct electromagnetic field inside the pipe is attenuated rapidly by circumferential eddy currents induced in the conducting pipe wall. The indirect field diffuses radially outward through the pipe wall. This field spreads rapidly along the pipe with little attenuation.

These two fields re-diffuse back through the pipe wall and are dominant at the remote field zone. Any discontinuities in the indirect path will cause changes in signal magnitude and phase. This technology does not require the sensors to be in close contact to the pipe wall. (B. Mergelas, X. Kong, 2001)

![Fig. 2.4 The principle of remote field eddy current testing.](Adapted from Z. Liu, Y. Kleiner, 2013)
B. Mergelas, X. Kong (2001) reported that prestressed concrete cylinder pipes (PCCPs) have two metallic elements, namely a steel cylinder and steel prestressing wire that is wrapped tightly around the core concrete to provide it with resistance to tensile stresses. Both metallic elements interact with the induced magnetic field. The interaction between the indirect transmission path and the prestressing wire is known as transformer coupling (TC). Thus, the received signal consists of two components, a remote field component and a transformer coupling component. The presence of broken wires will reduce the response of the transformer coupling component, thus allowing their detection. This technique requires a highly skilled person to analyze and interpret the amplitude and phase signals. The amplitude represents the strength of the transmitted signal while the phase represents the time that the signal takes to arrive at the detector.

The commercial RFEC/TC and P-Wave systems are widely used for detecting broken wires in prestressed concrete pipes. The See Snake tool is applied to small-diameter ferromagnetic pipes. The Pipe driver RFEC tool can be used to inspect large-diameter ferromagnetic pipes. Proprietors do not publish information about reliability and performance; however, RFEC seems to be the prevailing technology in the drinking water industry for inspection of ferromagnetic pipes and ferromagnetic components in composite pipes.

**C-Broadband electromagnetic (BEM):**

Unlike the conventional eddy current technique, which uses a single frequency for testing, the broadband electromagnetic technique transmits a signal that covers a broad frequency spectrum ranging from 50 Hz to 50 kHz. A transmitter coil passes an alternating current to the pipe surface, which generates an alternating magnetic field. (G. Hazelden, G. Ragula, M. Roubal, 2003)

Flux lines from this magnetic field pass through the metallic pipe wall, generating a voltage across it. This voltage produces eddy currents in the pipe wall, which induce a secondary magnetic field. Wall thickness is indirectly estimated by measuring signal attenuation and phase delay of the secondary magnetic field. BEM technology has been primarily used for condition assessment of water mains. It can only be used on ferrous materials to measure wall thickness, quantify graphitization, and locate broken wires in PCCP. (C.S. Feeney, S. Thayer, M. Bonomo, K. Martel, 2009)

Commercial BEM system and hand-held tool based on the same principle are available from the same technology vendor to measure corrosion pits. The BEM system is being further modified to facilitate the inspection of pipes exposed in keyhole excavations. This will help acquire information about pipe condition without disrupting service or full access excavations.

**d-Pulsed eddy current (PEC) testing:**

Pulsed eddy current is a method to determine wall thickness of insulated and non-insulated steel pipelines by external inspection. A rectangular shape eddy current is
generated by a transmitter coil. Each cycle consists of one positive and one negative pulse. The strength of the eddy currents is measured at some distance from the pipe wall (e.g., due to lift off or insulation thickness) by quantifying the magnetic reaction field picked up by the receiver coil. The strength is related to wall thickness. The average thickness of the metal is computed by comparing the transient time of certain signal features with similar calibrated signals. (C. Waters, Rtd-incotest, 2005)

The contact between the magnetic field and the inspected component produces a footprint that represents the area inspected for wall thickness calculation. The diameter of the footprint varies between 25 and 150mm, depending on wall thickness, insulation thickness and sensor size. The inspection tool is compact and can be easily deployed by remotely operated vehicles. Commercial PEC system has been used for inspection of insulated pipe/vessels in chemical plants and the oil and gas industry. (Z. Liu, Y. Kleiner, 2013)

e-Ground penetrating radar (GPR):

S.B. Costello, D.N. Chapman, C.D.F. Rogers, N. Metje (2007) reported that ground penetrating radar antennae transmit electromagnetic wave pulses into the ground. These pulses propagate through the ground and reflect off sub-surface boundaries. The reflections are detected by a receiving antenna and subsequently interpreted. Significant work needs to be done to process GPR data and signals.

Conventional GPR systems are operated from the ground surface. In-pipe GPR systems were also reported. Such systems use two or three antennae with different frequencies to investigate the structure of the surrounding soil, the interface between the soil and pipe, and the structure of the pipe. GPR can potentially identify leaks in buried water pipes either by detecting underground voids created by the leaking water or by detecting anomalies in the depth of the pipe as the radar propagation velocity changes due to soil saturation with leaking water. The GPR technique was also applied to determine the degree of internal leaching of hydroxides in asbestos-cement (AC) pipes. (P.G. Slaats, G.A. Mesman, L.P. Rosenthal, H. Brink, 2004)

Conventional GPR systems are commercially available. A prototype ground penetrating imaging radar (GPIR) was recently developed within a European Commission supported project ‘‘WATERPIPE’’ [25]. This high resolution GPIR is designed to detect leaks and image damaged regions in pipes. The capabilities of this high resolution GPIR reportedly include:
- Locate water pipe of all types of materials.
- Detect leaks and damages in water pipelines of all types of materials.
- Penetrate the ground to a depth of up to 200 cm.
- Achieve an image resolution of less than 50 mm.
- Survey velocity at approximately 0.36 km/h.

The measurement results currently available were obtained in a laboratory environment. The inspection results were used to assess the structural reliability, leakage, and conformity to water quality standards of the pipes. (Z. Liu, Y. Kleiner, 2013)
f-Ultra-wideband (UWB) pulsed radar system (P-Scan):

The P-Scan is based on UWB antennae capable of transmitting and receiving electromagnetic pulses in the nano- and pico-second ranges. For the inspection of buried pipes, it is desirable to operate in the picoseconds range because pulse widths in this region are equal to or less than the wall thickness of most non-ferrous buried pipes. The pulse repetition frequency (PRF) ranges from thousands to several billion pulses per second. Numerical experiments demonstrated the potential of this technique for pipe condition assessment. The use of ultra-short duration pulses makes it possible to obtain relatively high resolution results. Numerical simulation for P-Scan has been carried out and a pre-commercial prototype is still under development and not available yet. (E. Allouche, N. Simicevic, 2007)

2.4.1.3 Acoustic methods:

a- Sonar profiling system:

Z. Liu, Y. Kleiner (2013) stated that sonar is an acoustic detection technology designed to operate under water. In the pipe inspection field, it has been adapted to provide information about elements in the pipe that are submerged below the water line. These may include submerged debris in the pipe (sewers), grease level (sewers), differential settling and other submerged deformations and defects. A sonar system may consist of an underwater scanner unit, collapsible sonar siphon float, sonar processor/monitor, skid set, and all necessary interconnect cables. It typically travels in the pipes at velocities in the range of 0.1–0.2 m/s and sends a pulse about every 1.5 s. Each pulse provides an outline of the cross-section of the submerged part of the pipe.

Accurate measurements can be performed based on these outlines. The sonar profiling system can be used with different frequencies to achieve different goals. High frequency sonar can provide a higher resolution scan but a high resolution pulse attenuates quickly and therefore has a relatively low penetration capability. In contrast, low frequency sonar has a high penetration capability but is limited in its scanning resolution. Consequently, whereas high frequency sonar can be suitable for clear water conditions, turbid water with high concentrations of suspended solids may require a lower frequency signal. Small defects are more likely to be observed by a high frequency signal. Some systems are capable of a multi-frequency scan to obtain maximum information. A system that integrates sonar and video for use in submerged and large semi-submerged pipelines is also available. The cost of sonar inspections varies depending on the diameter of the pipe to be inspected.
b- Impact echo:

Impact echo testing is based on the use of impact-generated stress waves that propagate through and are reflected by the object under test. The impact echo equation is:

\[ T = \frac{V}{2F_p} \]

Where \( T \) is thickness, \( V \) is wave speed and \( F_p \) is peak frequency.

The time domain test data of the impulse hammer and accelerometer are transformed to the frequency domain as illustrated in Fig. 2.5. A transfer function is computed between the hammer and receiver as a function of frequency. Peaks in the transfer function reflect the effective thickness of the pipe wall at the test location. A more complicated model would be required to discern other properties of the object under test from frequency responses. Impact echo is typically applied to concrete, stone, plastic, masonry materials, wood and some ceramics. Various instruments are commercially available. Testing is conducted by hitting the test surface at a given location with a small instrumented
impulse hammer or impactor and recording the reflected wave with a displacement or accelerometer sensor adjacent to the impact location. (D.A. Sack, L.D. Olson, 1998)

The accelerometer is usually mounted to or pressed against the test surface. Frequency domain analysis is complicated when information other than thickness and geometry is needed and experience is required. Embedded items may affect wave behavior and test results. This method is not limited by pipe size and can be applied both internally and externally only if the testing is executable.

**C-SmartBall:**

SmartBall, a commercially available system, comprises a range of acoustic sensors, as well as an accelerometer, magnetometer, ultrasonic transmitter, and temperature sensors. It travels with the water flow down a pipe and detects, locates, and estimates the magnitude of leaks as it rolls. All the sensors are encased in an aluminum alloy core with a power source and other electronic components. The core is encapsulated inside a protective outer foam shell or sphere. The outer foam shell provides additional surface area to propel the device and also eliminates the noise that the device might generate while traversing the pipeline. The diameter of the outer sphere depends on the pipe diameter and flow conditions. The SmartBall is deployed into the water flow of a pipeline and captured at a downstream point. It continuously records acoustic data and emits an acoustic pulse every 3 s for tracking purpose, while the device traverses the pipeline. A SmartBall acoustic receiver, which is a patented technique, is used to track the location of the device. (R. Fletcher, 2008)

The above-ground markers can be placed at 2 km intervals and leak locations can be determined within 1 m. The recorded acoustic data are analyzed to identify air pockets and leaks. Air pockets and leak locations are determined using the other sensors attached to the SmartBall, e.g., accelerometer, temperature and pressure sensors. The severity of leaks is estimated by calibrated baseline data. Frequency analysis needs to be carried out to confirm that an acoustic anomaly is actually a leak. SmartBall is a relatively new technology and has seen significant entry into the marketplace. Further development of SmartBall technology for nature gas pipeline applications was supported by research funding from the U.S. Department of Transportation Pipeline and Hazardous Safety Administration. (S.T. Ariaratnam, M. Chandrasekaran, 2010)

**d-Sahara system:**

B. Mergelas, G. Henrich (2005) said that The Sahara system uses a hydrophone tethered to an umbilical cable, which travels inside in-service water mains, to record leak noises. A locator beacon can be tracked on the surface, enabling leaks to be marked for excavation and subsequent repair. Sahara locates leaks through identifying the distinctive acoustic signals generated by leaks in the pipe wall, the joints or steel welds. The magnitude of the leaks can also be estimated from the acoustic signal. Gas pockets in the pipeline are also detected by their unique acoustic signature. A video and lighting sensor
is also available on the Sahara platform to provide CCTV inspection of in-service potable water pipelines. Wastewater force mains have also been successfully inspected by flushing the line with clean water during the inspection. An average wall thickness calculation across set intervals of pipe (typically 9 m/30 ft) is also offered based on speed of sound measurements taken with the Sahara system. (Z. Liu, Y. Kleiner, 2013)

Fig. 2.6 The principle of LeakFinderRT for leak detection (adapted from Z. Liu, Y. Kleiner, 2013)

e- Leak detection:

As illustrated in Fig. 2.6, the LeakFinderRT system is composed of leak sensors, a wireless signal transmission system, and a personal computer. Acoustic sensors, such as accelerometers or hydrophones, are attached to two contact points on the pipe, such as fire hydrant. Accelerometers are used to sense leak-induced vibration while hydrophones are used for sensing leak-induced sound in the water column. Accelerometers are sensitive to background noise and hydrophones are often used together with accelerometers to achieve a better signal to noise ratio. The computer calculates the cross-correlation function of the two leak signals to determine the time lag $\tau_{\text{max}}$ between the two sensors. Then the location of the leak can be derived from the equations below:

$$L_1 = \frac{D - Ct_{\text{max}}}{2}$$

$$L_2 = D - L_1$$

Where $L_1$ and $L_2$ are the positions of the leak relative to sensors 1 and 2, respectively; $c$ is the propagation velocity of sound in the pipe; $D$ is the distance between location 1 and 2.
Propagation velocity needs to be determined experimentally or is estimated based on the type and size of the pipe. LeakfinderRT uses an enhanced cross-correlation function that is calculated indirectly in the frequency domain using the inverse Fourier transform of the cross-spectral density function rather than using the shift-and-multiply method in the time domain. The enhanced correlation function provides improved resolution for narrow-band leak signals. This is very helpful for plastic pipes (low frequency sound emission), small leaks, multiple leaks and situations with high background noise. Moreover, a major advantage of the enhanced function is that it does not require the usual filtering of leak signals to remove interfering noises. (O. Hunaidi, A. Wang, M. Bracken, T. Gambino, C. Fricke, 2004)

Based on principles similar to LeakfinderRT, a technique, ‘‘Wall Thickness Finder’’ was developed to estimate the average pipe wall thickness between two listening points on the pipe. The average thickness of the pipe section between two acoustic sensors can be back calculated from a theoretical model, which incorporates the acoustic velocity, pipe diameter, Young’s modulus of the pipe wall, and the bulk modulus of elasticity of water. Velocity measurement can be performed with the same hardware as LeakfinderRT by using the cross-correlation method. (O. Hunaidi, 2006)

Signals from leak sensors can be transmitted wirelessly to a computer for processing. Leak sounds are recorded and correlated by LeakfinderRT in a few minutes under most circumstances, but noisy records can take longer to process. The cross-correlation results are displayed on screen and are continuously updated in real time while leak signals are being recorded.

2.4.1.4 Ultrasound methods:

a- Guided wave ultrasound:

The guided wave ultrasound technique is based on the capability of propagating a wave for a long distance (J.L. Rose, J. Mu, Y. Cho, 2008). The name of a guided wave depends on the structure type and how energy is transmitted through the structure. Torsional waves travel via a shearing motion parallel to the circumferential direction. The attenuation by water and coatings is less for shearing motion. Longitudinal waves travel via flexural/compressional motion in the radial and axial directions and can be easily affected by water and coatings. Depending on the type of guided wave, the number of transducers can range between two and four. Torsional waves require two transducers while longitudinal waves require three to four transducers. The torsional guided wave transducers operate in a pulse-echo configuration where the transducers are used for both excitation and detection of the signals. Torsional or longitudinal guided waves are induced into the pipe and propagated along the length of the pipe segment. A torsional wave system can be used in pipes filled with water while the longitudinal system cannot. In a longitudinal system, three transducers can only operate on a single frequency. Multiple frequencies can be applied if four transducers are used; this arrangement leads to an improved inspection result. When these guided waves encounter an anomaly or pipe feature, laminar waves reflect back to the transducer’s original location. The time-of-
flight for each signature is calculated to determine its distance from the transducer. The amplitude of the signature determines the size significance of the defect.

A probe in the form of a ring array of piezoelectric transducers is clamped around the pipe and an ultrasound is sent simultaneously in both directions along the pipe (Fig.2.6 a). The acquired signal is similar to conventional ultrasound testing (UT) A-scans. The horizontal axis represents the distance along the pipe while the vertical axis represents signal magnitude, which can be used to characterize metal loss due to the corrosion. This technique is suitable for pipes above 50 mm in diameter and wall thicknesses up to 40mm. Inspection for an elevated pipe can be conducted for a range of up to 30 m in either direction from a specific spot where the probe is placed. (Z. Liu, Y. Kleiner, 2013)

The guided wave system was originally designed for use on above-ground exposed or insulated pipes. It has been applied to buried pipes, but the range of inspection will be shorter due to the rapid attenuation of the signals. The use of non-contact and couplant-free electromagnetic acoustic transducer (EMAT) was also reported (W. Luo, J.L. Rose, 2003). The commercial system is available from many vendors and consulting companies.

![Guided wave ultrasound testing](image1)

![Discrete ultrasound testing](image2)

**Fig. 2. 7** The ultrasound testing: (a) guided wave ultrasound testing and (b) discrete ultrasound testing. (adapted from Z. Liu, Y. Kleiner, 2013)

**b- Discrete ultrasound:**

Discrete ultrasonic measurement transmits a high-frequency short wave through a couplant to the material being tested (Fig.2. 6 b). The wave can be generated by several methods, including piezoelectric ceramics, electromagnetic acoustic transducer, magnetostrictive sensor, laser and piezoelectric polymers. The waves propagate to the back wall of the specimen and are reflected back towards the transducer. Transition time is recorded and used in combination with the velocity of the wave propagating in the material to compute the travel distance of the wave. Materials with known thicknesses are used to calibrate the sensor.
A typical UT system consists of a pulser/receiver, transducer, and display unit. Driven by the pulser, the transducer generates a high frequency ultrasonic energy that propagates through the materials in the form of waves. When an object is encountered in its path, part of the energy is reflected back from the object’s surface. The reflected wave is transformed into an electrical signal, from which information on the reflector’s location, size, orientation, and other features can be inferred. Types of ultrasonic system displays include:
- A-scan: discontinuity depth and amplitude of signal.
- B-scan: discontinuity depth and distribution in cross sectional view.
- C-scan: discontinuity distribution in plain view.
The three types of UT signal representation are illustrated in Fig.2.8

UT inspection of pipes can be done both externally and internally. Usually, UT inspection needs couplant or water to transmit the wave between the transducer and the pipe wall. However, the electromagnetic-acoustic transducer (EMAT) does not need couplant. The UT system is available from many companies. (Z. Liu, Y. Kleiner, 2013)

![Fig.2.8 The representation of UT signals (adapted from Z. Liu, Y. Kleiner, 2013)]
c- Phased array technology:

For conventional UT, the shape of a sound beam and its travel direction are fixed for each sensor. An array transducer contains a number of individual elements in a single housing. With phased array technology, it is possible to program virtual sensor arrangements, which can send sound beams with different characteristics and in different directions, i.e. the aperture, shape, and direction of the ultrasound beam can be controlled. The central elements of this technology are arrays built up of composite sensor elements that are controlled individually by the ultrasound electronics (J. Bosch, A. Hugger, J. Franz, S. Falter, 2004). A set of neighboring composite sensor elements is triggered simultaneously. The sound beam and its direction are determined by how the composite sensor elements are triggered.

Phased arrays use an array of sensor elements, all individually wired, pulsed, and time shifted. (P.O. Moore, 2007) The elements can be organized as a linear array, a two-dimensional matrix array, a circular array or in other more complex forms. Any set of sensor elements can be used as a virtual sensor. For instance, a virtual wall thickness measurement sensor can be built up by a group of composite sensor elements. If these elements are triggered simultaneously, a sound beam perpendicular to the wall surface is generated, as illustrated in Fig.2.9. If the neighboring elements are triggered with a certain time shift from element to element, an angular sound beam is generated. A virtual crack detection sensor comprises a group of such sensor elements. The major advantage of the phased array technology is its capability on interpreting complex defects, such as discrimination between cracks and metal loss, and identification of hook cracks (J. Bosch, A. Hugger, J. Franz, S. Falter, 2004). The technical features of phased array ultrasonic technology include:

- Multiplexing of a large number of identical crystals as a single probe.
- Control of the focal depth.
- Control of the steering angle.
- Control of the beam width.
- Program of the virtual probe aperture.
- Scan with a large number of A-scans.
- Display of the UT data in a generic view named S-scan.

The phased array UT is commercially available and continually undergoing further development, but the application to water mains has not been reported yet.
Fig. 2.9 Sound beams generated by phased array of composite sensor elements (adapted from J. Bosch, A. Hugger, J. Franz, S. Falter, 2004)

**d- Combined UT inspection:**

A combined UT technique, which can simultaneously quantify metal loss and detect cracks, was reported in. This technique uses a newly designed and optimized sensor carrier to perform both inspections in a single run. A sufficient number of UT sensors are placed to cover the circumference of the pipe. These sensors work in a pulse-echo mode with a high repetition frequency. Straight incidence of the ultrasonic pulses is used to measure the wall thickness and 45° incidence is used for the detection of cracks. Although this technique was developed for gas and oil pipelines, it may also be a promising tool for water mains. (M. Beller, A. Barbian, 2006)

**2.4.1.5 Radiographic methods:**

Radiographic testing uses a source of radiation, either gamma or X-rays, which passes through the material and onto a photographic film. There are three basic setups for radiographic testing in the water sector as illustrated in Fig. 2.10. The density changes on the film indicate possible imperfections. Nowadays, digital cameras have been used to replace film, but they are limited by the size of the complementary metal-oxide-semiconductor (CMOS) photodiode array in the image sensor.

X-rays created by cathode-ray tubes are used for plastic materials. Details of the material structure can be seen on the radiograph. However, it has technical limitations in that pipes of 38.1 cm diameter and greater must be emptied. The inspection of valves is with conventional film based radiography. Darker areas correspond to thinner or less dense material. Typical defects that can be detected include:

- Pits in ferrous materials. Corrosion products are less dense and appear darker on the radiograph.
- Voids in cementitious materials.
- Inclusions or manufacturing voids.
Gamma rays emitted from isotopes are used for ferrous and cementitious materials. Gamma radiography has been used to check welds in oil and gas pipelines. A recent commercial development is the backscatter computed tomography (BCT), which does not require film on the other side of the inspected object [45]. This technology is currently being applied to the inspection of culvert, corrosion under insulation; fiberglass reinforced plastic (FRP) infrastructure, and structures in aerospace applications.

![Radiographic method](adapted from Z. Liu, Y. Kleiner, 2013)

### 2.4.1.6 Thermography methods:

Thermographic testing is a non-contact method of detecting thermal anomalies. Infrared radiation has a longer wavelength than visible light (>700nm). Any object above 0 K radiates infrared energy and the amount of radiated energy is a function of the object’s temperature and emissivity, which is a measure of the surface efficiency in transferring infrared energy. Areas with different thermal masses will have different rates of heat absorption and radiation. The infrared radiation is converted into a visible image and tested objects can be distinguished on the basis of their heat emission. (Z. Liu, Y. Kleiner, 2013)

In thermographic testing, an external heat source is typically used to heat the inspected object as illustrated in Fig. 2.11. Subsequently, the object’s cooling characteristics are monitored by an infrared camera and these characteristics are then interpreted to discern object properties. (B. Crouse, 2009) Varied active thermographic testing methods, which use a heat source to obtain the desired thermal contrast, have been developed for different applications. These methods include pulse thermography, stepped heating thermography, lock-in thermography, and vibro-thermography. All the testing systems are commercially available.
Fig. 2.11 The pulse thermography testing. (adapted from Z. Liu, Y. Kleiner, 2013)

Table 2.2: Summary of the performance of condition assessment technologies. (Adapted from Z. Liu, Y. Kleiner, 2013)

<table>
<thead>
<tr>
<th>Condition assessment technologies</th>
<th>Description of performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>Depends on skills of personnel</td>
</tr>
<tr>
<td>Laser scan</td>
<td>The laser profiling is accurate, but still needs data processing to compensate for errors introduced during scanning. Report on performance study is not available</td>
</tr>
<tr>
<td>Magnetic flux leakage</td>
<td>The MFL test needs to be calibrated to interpret the acquired signal. It is mainly used for detecting corrosion pits and small defects. The detection of pipe wall remaining thickness is quite accurate</td>
</tr>
<tr>
<td>Remote field eddy current</td>
<td>Proprietors do not publish information about false positives/false negatives; however, RFEC seems to be the prevailing technology in the drinking water industry for inspection of ferromagnetic pipes and ferromagnetic</td>
</tr>
<tr>
<td>Method</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Broadband electromagnetic</td>
<td>The mean value of wall thickness is measured for a square grid. A surface scratch or an isolated pit smaller than the square grid will not be detected.</td>
</tr>
<tr>
<td>Pulsed eddy current</td>
<td>The instrument is capable of high accuracy and good repeatability.</td>
</tr>
<tr>
<td>Ground Penetrating Radar</td>
<td>The performance of GPR is highly dependent on soil conditions. No evidence of consistent ability to detect voids with GPR. Substantial operator interpretation of results is necessary.</td>
</tr>
<tr>
<td>Ultra-wideband pulsed radar system</td>
<td>Not yet determined.</td>
</tr>
<tr>
<td>Sonar profiling</td>
<td>Can generate precise pipe cross-section via dwell scan.</td>
</tr>
<tr>
<td>Impact echo</td>
<td>Accuracy is typically 2% at high resolution when properly calibrated on a known thickness location. The typical thickness for the impact echo testing ranges from 66 mm to 1.8 m.</td>
</tr>
<tr>
<td>SmartBall</td>
<td>As reported by Pure Technologies, the device can detect leaks of less than 0.026 L/h (0.1 gal/h) under ideal conditions (high pressure and low levels of ambient noise). Location accuracy depends on how well the configuration of a pipeline is known. Typically, the location accuracy of the device is within 1 m.</td>
</tr>
<tr>
<td>Sahara system</td>
<td>Buried unknown leaks as small as 0.25 gal per hour have been successfully located. The accuracy of locating a leak is generally less than 1 m.</td>
</tr>
</tbody>
</table>
| Leak detection                 | The performance of the LeakfinderRT™ system has been successfully tested for the following scenarios:  
- Narrow-band leak noise in PVC pipes  
- Small leaks in PVC pipes under a very low pressure of 20 psi  
- Locating small leaks in metal pipes  
- Effective for situations with high background noise  
- Improved peak definition for resolving multiple leaks  
- The smallest PVC pipe leaks detectable with LeakfinderRT™'s low frequency vibration sensors (1.7 L/min) and hydrophones (0.85
Theoretical leak location error is less than 10 cm. Actual error depends on accuracy of sensor spacing and propagation velocity. The distance between acoustic sensors is determined by the pipe materials and size.

The monitoring duration depends on the quality of the signal. More signal with much noises need a longer monitoring time.

<table>
<thead>
<tr>
<th>Ultrasound methods</th>
<th>Guided wave ultrasound</th>
<th>Sensitivity can be as good as 1% loss of cross-section in ideal conditions (but is typically set at 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Discrete ultrasound</td>
<td>Can achieve a reasonable degree of accuracy for the remaining wall thickness measurement</td>
</tr>
<tr>
<td></td>
<td>Phased array technology</td>
<td>Phased array technique can optimize discontinuity detection while minimizing test time</td>
</tr>
<tr>
<td></td>
<td>Combined UT inspection</td>
<td>Not available for water main condition assessment</td>
</tr>
<tr>
<td>Radiographic methods</td>
<td></td>
<td>Can provide accurate measurements, but experience is required to interpret the inspection results</td>
</tr>
<tr>
<td>Thermography methods</td>
<td></td>
<td>The infrared sensor is sensitive and reliable</td>
</tr>
</tbody>
</table>

2. 4.2 indirect methods for pipe inspection:

2. 4.2.1 linear polarization resistance (LPR) of soil:

An electrochemical reaction with a weak electrical current is produced when a metal is immersed in an electrolyte solution, which leads to the corrosion of metal. The rate of corrosion is directly proportional to this current and inversely proportional to the electrical resistance (polarization resistance) of the metal/electrolyte pair. The direct measurement of corrosion current in the soil solution (electrolyte) is very difficult. Instead, it can be inferred by imposing a weak electrical potential (10–20 mV) between two electrodes. This potential produces small currents that are linearly proportional to actual corrosion current. The ratio between the imposed electrical potential and the resulting current provides the property known as the polarization resistance which, at low potential values, is nearly linear to the corrosion current. It should be noted that LPR is an inferential indicator of pipe corrosion as defined previously. Portable LPR instruments are commercially available from several companies. It allows the assessment of corrosion rate in real time. (Z. Liu, Y. Kleiner, 2013)
2. 4.2.2 Soil characterization:

D. Marlow, S. Heart, S. Burn, A. Urquhart, S. Gould, M. Anderson, S. Cook, M. Ambrose, B. Madin, A. Fitzgerald (2007) said that soil characterization is used to explore the soil parameters relevant to the deterioration of buried pipes. Samples from the locations near the pipe are collected for lab characterization or in situ testing. The following is a list of the main soil parameters of interest:

- **Soil resistivity**: Low resistivity is likely to have high corrosion rates.

- **pH value**: Low pH value (<4) is generally associated with corrosion of ferrous assets and deterioration of cementitious assets. However, high alkalinity soils (pH > 8) can also lead to high corrosion of metallic pipes as well as prestressing wire and steel cylinder in PCCP.

- **Redox potential**: The redox potential of soil is a measure of soil aeration and provides an indication of the suitability of conditions for sulfate reducing bacteria. High availability of oxygen promotes microbial induced corrosion (MIC) in the presence of sulfates and sulfides.

- **Sulfates**: Sulfates react with cementitious materials, forming gypsum and ettringite. Sulfate attachment only occurs where the sulfate salts are in solution.

- **Chloride content**: Chloride ions permeate into cementitious and attached steel reinforcement. Presence of chloride ions in moist soil act as electrolyte and reduce soil resistivity, which encourages corrosion in metallic pipes, where the metal is in contact with the soil. In the case of PCCP (steel encased in concrete), if there are cracks in the outer mortar layer, ingress of chlorides in the presence of oxygen will promote corrosion in the prestressing steel wire as well as in the steel cylinder.

- **Moisture content**: Soil moisture acts as the electrolyte in electrochemical corrosion of ferrous pipes. It also defines the degree of soil saturation.

- **Shrink/swell capacity**: High shrink/swell capacities are known to have an increased failure rate due to the stresses imparted by the soil during the shrink/swell cycle.

- **Buffering capacity**: A soil’s buffering capacity is the degree to which it is able to resist changes in pH in particular acidification.

- **LPR**: High LPR indicates low corrosion rates. The corrosion rate can be roughly estimated from LPR measurements.

- **Contaminants**: Soil contaminants can have negative effects on polymeric materials. High levels of acidic contents can also cause environmental stress cracking.
-Soil compaction: The susceptibility of the trench filling and the surrounding sediments for compaction.

It should be noted that soil corrosivity is not a directly measurable parameter nor is there an explicit relationship between the soil corrosivity and soil properties. A number of empirical approaches have been proposed in literature to consider some or all of the above listed parameters in the determination of soil corrosivity and potential pipe deterioration. (Z. Liu, R. Sadiq, B. Rajani, H. Najjaran, 2010)

2. 4.2.3 Pipe to soil potential survey:

Pipe-to-soil potential reflects the interaction between ferrous pipes and the surrounding soil. The measurement can be done with a voltmeter and a reference electrode. There are two types of pipe potential survey. The first is the direct current voltage gradient (DCVG) survey that can be used to determine the location of gaps in a pipe’s protective coating. A direct current is introduced to the pipe and the difference between two reference electrodes is measured in the pipe-to-soil voltage. The two electrodes are gradually moved along the whole length of the pipe. If a gap exists in the coating, there will be a significant increase in voltage gradient compared with the gradient found when the coating is intact. The second type of potential survey consists of using a single reference electrode (Cu/CuSO4) without an imposed current to determine the pipe-to-soil potential along the pipe. The pipe-to-soil potential can be used to estimate corrosion rate with calibration data. Calibration is carried out by directly assessing the external conditions of mains in different soils. In order to acquire enough soil information to calculate corrosion rate, the soil needs to be sampled at every 50 or 100 m. It should be noted that potential survey reflects a propensity for corrosion rather than actual corrosion. (Z. Liu, Y. Kleiner, 2013)

2. 4.3 Indirect Indicators:

Best Practices (2003b) stated that the best way to preliminary assess the condition of a water distribution system is through analyzing the available data, which should be sufficient to be statistically significant. They specify the type of data that should be used to conduct such analysis based on four common types of problems that can occur in water distribution systems: structural condition, hydraulic capacity, leakage, and water quality problems. The type of data that should be used is summarized in Table 2.3. The preliminary assessment will assist municipal engineer in identifying the trends of failure for pipes in water system, and hence be able for locating and prioritizing areas that need more detailed investigation.

2. 4.3.1 Structural Condition:

A preliminary assessment of structural condition in a distribution system is based on analyzing the total number of breaks/year. However, the acceptable total number of
breaks/year varies from one municipality to another. The location of all breaks can be presented on a geographic information system (GIS) map to verify areas with higher break frequency than others. It can also be presented on a global positioning system (GPS) map to conduct spatial analysis. That is done by overlaying break records location on a soil map to verify the correlation between soil types and break frequency (Best Practices, 2003b).

2. 4.3.2 Hydraulic Capacity:

A preliminary assessment of hydraulic capacity in a distribution system is based on analyzing low-pressure complaints and hydrant-flow test results. The analysis of the collected data will show the trend of hydraulic capacity changing through the distribution system over time and how it varies spatially. If the numbers of low-pressure complaints or low fire flows records are increased over the time, it indicates that the hydraulic capacity of a system is deteriorating. That is due to tuberculation in the mains or partially closed isolation valves (Best Practices, 2003b).

2. 4.3.3 Leakage:

Best Practices (2003b) reported that leak detection can be an important tool to determine the deterioration of water distribution systems. Leakage testing technique is based on determining the amount of leakage from the mains at a known pressure. The most common methodologies that are used to detect the leakage of the water system are hydrostatic leakage test and water audits. They have been applied in the past to significant portions of or entire water distribution systems.

2. 4.3.4 Hydrostatic Leakage Test:

The testing is done by isolating the system into zones or pipeline segments, and measuring the amount of water added to the mains to maintain the test pressure which varies according to working pressure of the inspected pipeline. Then, the rate of leakage is measured. If the rate of leakage is more than the expected allowable leakage rate according to specification; then there is a pipe failure (Comeau et al. 2000; Makar et al., 2000).

2. 4.3.5 Water Audit:

The City is divided into sections. For each section, total consumption is measured, and the total industrial consumption and consumption/hour hold is evaluated. The difference is an indication of existence leaks. It can be combined with leak detection approach. In some cases the water audits are performed and organized continually with automatic data recording system in order to facilitate quick repairs for the leaking pipes (Makar et al., 2000).
2. 4.3.6 Water Quality:

A preliminary assessment of the water quality in a distribution system is based on analyzing the water quality complaint records and routine water quality monitoring data. The analysis of the collected data will show the trend of water quality changing through the distribution system over time and how it varies spatially. Chlorine residuals and concentration of iron in water are used as a measure for water quality. When chlorine residuals are decreased in some areas of water system, it indicates that these areas are deteriorating. Likewise, the concentration of iron is increased in water indicates the degree of internal corrosion of unlined metallic mains (Best Practice, 2003b).
<table>
<thead>
<tr>
<th>Problem</th>
<th>Preliminary Assessment</th>
<th>Reasons For More Detailed Investigation</th>
<th>Detailed Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Condition</strong></td>
<td>- Spatial and temporal analysis of water main breaks - Compilation of soil map - Routine inspection of valves and hydrants - Routine inspection of insulation and heat tracing in northern areas</td>
<td><strong>Level of Service</strong> - Preliminary investigations indicate an excessive break rate, excessive leakage, inadequate hydraulic capacity and/or impairment of water quality</td>
<td>- Detailed analysis of break patterns, rates and trends - Statistical and physical models - Pipe sampling - Soil corrosivity measurements - Pit depth measurements - Non-destructive testing - Failure analysis - Visual inspection • Thermal analysis (far North)</td>
</tr>
<tr>
<td><strong>Hydraulic Capacity</strong></td>
<td>- Low-pressure complaints - Hydrant flow tests - Rusty/coloured water occurrences - Visual inspection of pipe interior - Monitoring of pressure and pumping costs</td>
<td><strong>Cost Effectiveness</strong> - To facilitate capital planning and asset management programs</td>
<td>- Hazen-Williams C factor tests (pipe roughness) - Computer modeling</td>
</tr>
<tr>
<td><strong>Leakage</strong></td>
<td>- Water use audit - Per capita water demand - Routine leak detection survey</td>
<td><strong>Risk Management</strong> - Risk analysis identifies Critical water mains that have a high potential for significant Property damage, environmental impact or loss of service</td>
<td>- Leak detection survey - Detailed limited area leakage / demand assessment</td>
</tr>
<tr>
<td><strong>Water Quality</strong></td>
<td>- Water quality complaints - Routine sampling data - Results of flushing Program - Due diligence (e.g., failure analysis of a failed critical water main)</td>
<td></td>
<td>- Detailed water quality investigation - Computer modelling</td>
</tr>
</tbody>
</table>
2.5 Condition rating models:

Al- Barqawi and Zayed (2008) developed a model in order to assess the condition and predict the performance of water mains. An integrated model and framework, using an analytic hierarchy process (AHP) and artificial neural network (ANN), are developed. In addition, an automated, user-friendly, web-based infrastructure management tool (CR-Predictor) is developed based on the integrated AHP/ANN model to assess water main condition. Eleven subfactors are considered in the model (Type of soil, Type of traffic/road, Type of service, Ground water level, Pipe diameter, Pipe material, Pipe age, Breakage rate, C Factor, Cathodic protection, Operational pressure). Results showed that pipe age has the highest impact on condition assessment (20.95%); followed by pipe material (17.49%) and breakage rate (13.13%). On the other hand, the factor with the lowest impact is type of service (2.85%).

Al- Barqawi and Zayed (2006) used Artificial Neural Network (ANN) for make condition rating model of water mains. The ANN input factors incorporate pipe type, size, age, breakage rate, Hazen-Williams factor, excavation depth, soil type, and top road surface; however, the output is pipe condition. The results showed that the factor contributing most to the water mains condition is the breakage rate (30.17%); however, the second factor is age (13.56%). On the other hand, the factor contributing least is type of surface (5.91%).

Najafi and Kulandaivel (2005) developed a neural network (ANN) model for predicting the condition of sewer pipes based on the historic condition assessment data. Seven input variables used in the developed model including length, size, type of material, age, depth, slope, and type of sewer. The output of the model is the condition rating which scaled from“1” to“5”. “1” value indicates that the pipe is in perfect condition, and “5” value indicates that the pipe in poor condition. However, model validation is not done.

2.6 Deterioration models:

Wang, Zayed and Moselhi (2009) presented deterioration models that predict the annual break rates of water mains are able considering pipe material, diameter, age, and length. This model is based on the data collected from the municipality of Stefoy, Quebec city, Quebec, Canada. The annual break rate, pipe age, length, diameter, depth of installation, and material are used to develop multiple regression models that to forecast the annual break rate of a water main based on the aforementioned factors. The results show that pipe length has a great impact on the annual break rate. The annual break rates for short pipes are higher than those of larger lengths, while annual break rates increase as age increases.
The limitations in the developed models can be presented as follows:
1. The models cannot predict when the next failure is going to occur for a specific pipe.
2. The models do not account for past pipe repairs, cathodic protection, and soil conditions.

Rajani and Kleiner (2001) provide a comprehensive literature overview and criticism for the developed mechanical models, which are divided into two groups, deterministic and stochastic models. These models are appropriate to be applied for major transmission water mains. These physical mechanisms include three main aspects: (1) pipe structural properties (i.e. material type, pipe-soil interaction, and quality of installation); (2) internal loads due to operational pressure and external loads (i.e. soil overburden, traffic loads, frost loads and third party interference); and (3) material deterioration due largely to the external and internal chemical, bio-chemical and electrochemical environment.

Kleiner and Rajani, (2001) present a comprehensive literature overview and criticism for the developed statistical models which are classified mainly into 3 groups; deterministic, probabilistic multivariate, and probabilistic single-variate models. These models are appropriate to be applied for water distribution networks. They are used to quantify the structural deterioration of water mains based on analyzing various levels of historical input data, which identify pipe breakage patterns, and hence predict the breakage rate of a water main.