Review of Condition Assessment Techniques for Pressure Pipes for Water

Purvi Pancholy[1], Greg Preston[2], Theunis Henning[3], John Mackie[4] and Larry Bellamy[1]

1. *Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand*
2. *Quake Centre, Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand*
3. *Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand*
4. *Golder Associates (NZ) Limited, Christchurch, New Zealand*

This report is an output from the Quake Centre's Building Innovation Partnership program (BIP), which is jointly funded by industry and the Ministry of Business Innovation and Employment (MBIE). This report provides an overview of the technologies that are available for in-situ pressure water pipe condition assessment, and look to the future to provide insight into the technologies that are yet to be commercially available or are in an early stage of development.

International Reviewer

- Prof. Ian Moore – Queen's University, Kingston, Canada

Acknowledgements:

The Quake Centre would like to acknowledge the following for their valuable contribution to this project:

- John Mackie - Golder Associates (NZ) Limited
- Prof. Pedro Jose Lee – University of Canterbury
- Michael Galambos – Christchurch City Council
- Irmana Garcia Sampedro – Christchurch City Council
- Prof. Ian Moore – Queen's University, Kingston, Canada
- Dr Young-il Kim – Detection Services (Adelaide Office)
- Noel Roberts – Water New Zealand
- Lesley Smith – Water New Zealand
- Prof. Kobus van Zyl – The University of Auckland

Disclaimer

Executive Summary

This report generated by Quake Centre's Building Innovation Partnership (BIP) is intended to provide an overview of the technologies that are available for in-situ pipe assessment as well as look to the future to provide insight into the technologies that are yet to be commercially available or are in early stage development. This document will provide guidance to industry to select appropriate technology when investigating the condition of the pipe network.

This project involved researching and categorising condition assessment technologies for water and sewer mains. The summary table "Detailed summary of condition assessment techniques" provided in the Evaluation of Techniques section includes a definition of different available technologies, their advantages and disadvantages, suitable pipe material and diameter range, and applicability to water and wastewater utilities.

1 Introduction

1.1 Purpose

The purpose of this report is to investigate technologies for assessing the condition of New Zealand's pressurised water network – primarily fresh water conveyance systems, including transmission mains and water mains. The list included in this report is not intended to be exhaustive, but rather cover main areas of different available techniques.

1.2 Objectives

- Identify the effectiveness of the latest available technologies for pressure water pipe condition assessment, and look to the future to provide insight into the technologies that are yet to be commercially available or in an early stage of development;
- Evaluating commercially available techniques for pressure pipes for water based on their advantages, disadvantages, accuracy, cost effectiveness, and applicability to NZ's water and wastewater utilities;
- First step towards developing a standard manual for NZ's pressure pipes. Such a pipe inspection manual is available for gravity-flow pipes, however, for pressure pipes a standard manual is yet to be prepared; and
- To provide information to the water industry to select appropriate technology for assessing the condition of the pipe network. This may save unnecessary and expensive invasive pipe sampling investigations or reduce the risk of catastrophic failure with the associated costs.

1.3 Background

The Building Innovation Partnership (BIP) is an industry-led research program that supports transformations in the building and construction industry. BIP is initiating a number of projects in what is designated as Theme 1, Better investment Decision-making focusing initially on 3 water pipe networks. Several of these projects are directly related to the performance of pipes and the data that underpins the management of these asset and related decision-making.

Water infrastructure worldwide is facing a crisis of aging pipe infrastructure. Pipes and valves lose their physical integrity through deterioration over time or because of catastrophic events such as earthquakes. This results not only in community and business disruption but also in water losses, risk of contamination and the inability to isolate a section of pipe for repair. The complexity and extent of water supply systems, combined with the fact that they are buried underground, make their condition assessment a challenging infrastructure management problem. An appropriate approach of pipe asset management should involve tracking the decay of each pipe so that the assets are replaced at an optimum time in their life cycle, allowing managers to accurately forecast, budget and allocate expenditures over long planning cycles. Current barriers to this management approach lie in (1) the lack of understanding of the rate/processes of pipeline decay for pipes buried in various ground conditions and (2) the lack of a reliable, in-situ and repeatable method for condition assessment that will allow the pipe decay to be tracked over time.

New Zealand (NZ) is facing a crisis of aging pipe infrastructure and its water network is losing close to 20% of the water [1] it carries. Over the next decade, councils across the country may need to increase water infrastructure budgets by up to 30% to replace the network, with a total of $\$41$ billion [2] to be spent. Despite the level of investment, councils have struggled to formulate strategic pipe renewal programs due to the lack of reliable data on their pipe networks. Half of the NZ councils have indicated that they have low confidence in their pipe condition information [1] and extensive testing of current pipe condition rarely occurs due to slow speed and high cost of intrusive nature of assessment technologies. The current approach of assessing the condition of water pipes in NZ involves excavating the pipeline, and removing a section of the pipe to conduct material testing on the sample. This method (known as coupon sampling) is expensive, highly disruptive and rarely repeated for the same pipe. To overcome the problem, non-destructive field inspection techniques of condition assessment are required.

2 Overview of Pressure Pipe Systems

Pipes are widely used for water distribution and wastewater collection systems, generally found in urban residential, commercial and industrial areas. Pipeline networks can extend thousands of kilometres and consists of multiple pipe segments that are connected by joints. These pipelines are subjected to many incidents such as seismic effects, traffic and surface loads, poor workmanship, impact, pitting, corrosion and water hammer that may lead to a leak or burst in the pipeline. A leak incident in the pipeline may cause a sudden decrease in the pressure [3], that would cause inefficiency in terms of delivery time and the volume flow rate of water being transported. They also increase the risk of contaminants entering the de-pressurised system, thus creating a public health risk.

Sometimes, impurities and chemical processes can cause a reduction in hydraulic performance and disturb the usual flow in the pipe network. Blockages (either discreet or extended) may begin in the form of a small increase in the wall roughness that exacerbates with time due to physical, biological or chemical processes and can finally impinge a significant part in the internal cross-sectional area of pipe [4]. Insufficient flow of water causes reduction of service potential or eventual failure of the pipe network. Therefore, pipeline fault detection becomes the topmost priority within the water distribution management system.

This section describes details of the pressurised pipe system, including pipe network elements, types of valves, pumps, pipe materials, types of pipe failure, factors influencing pipe failures and an overview of the available pipe leak detection technologies.

2.1 Pressurised Pipe System

Liquid in motion produces forces and pressure whenever its velocity or flow direction changes. Knowing pipe pressure and flow at certain points along the pipe's path can help determine the necessary pipe size and capacity, as well as what pipe material would work best in given situations [5]. Understanding hydraulics can help decide what pipe flow rates related to size and material are necessary to transport water in an efficient manner.

When water flows in a pipe, friction occurs between the flowing water and the pipe wall, and between the layers of water moving at different velocities in the pipe due to the viscosity of water. For a Newtonian fluid (such as water) the flow velocity is assumed to be zero at the pipe wall (referred to as the boundary layer) and increases to its peak velocity at the centreline of the pipe. The frictional resistance to flow causes energy loss in the system.

Based on the Law of Conservation of Energy, fluid flowing in a pipe contains three energy components, namely: energy due to motion (*kinetic energy*), energy due to elevation (*gravitational potential energy*) and energy due to pressure (*pressure energy*). The total energy associated with the unit weight of the water is called head. Energy losses (i.e. head losses) are generally the result of two mechanisms: friction along the pipe walls and turbulence due to changes in streamlines through fittings and appurtenances. Head losses along the pipe wall are called frictional losses, while losses due to turbulence within the bulk water are called minor losses.

2.2 Pipe Types

Water is distributed to domestic, commercial, industrial, public, and sometimes irrigation users in different service zones. Pipelines are generally classified into three main types, namely transmission mains, water (distribution) mains and reticulation mains.

Transmission mains (Trunk Mains) are larger pipes which are designed to move larger quantities of water from the source of supply, such as a treatment plant or groundwater well, and provide water to the smaller distribution mains.

Water (distribution) mains generally regarded as mains within a network that are the primary source of delivery to storage facilities such as reservoirs, which generally are not used to provide individual connections.

Reticulation mains generally fed from distribution mains and deliver water to individual customers and for fire fighting.

Homes, businesses, and industries have their own internal plumbing systems to transport water to sinks, washing machines, hose bibbs, and so forth [6].

2.3 Valves and Appurtenances

2.3.1 Types of Valves

The primary purpose of valves in a water network is to isolate sections of pipe so that repairs and maintenance can be carried out with minimal interruption to customers. Commonly used types of valves in water distribution systems are:

Isolation valves: These types of valves can be manually closed to block the flow of water. The purpose of these valves is to provide a field crew with a means of shutting down a portion of the system to, for example, replace a broken pipe or repair a leaky joint [6].

There are several types of isolation valves that may be used, including gate valves, butterfly valves, and plug valves.

Directional valves: Also called check valves or non-return valves, are used to ensure that water can flow in one direction through the pipeline, but cannot flow in the opposite direction (they prevent back-flow). Any water flowing backward through the valve causes it to close, and it remains closed until the flow once again begins to go through the valve in the forward direction [6].

Altitude valves: Many water utilities employ these types of valves at the point where a pipeline enters a tank or reservoir. When the tank level rises to a specified upper limit, the valve closes to prevent any further flow from entering, thus eliminating overflow. The valve reopens when the water level in the tank lowers so that it can recommence filling.

Air Release and Vacuum breaking valves: Air release valves are used in most systems to release trapped air during system operation, and vacuum breaking valves are used to discharge air upon system start-up and admit air into the system in response to negative gauge pressure. These types of valves are often found at system high points, where trapped air accumulates, and at changes in grade, where pressures are most likely to drop below ambient or atmospheric conditions [6].

Control valves: Control valves are also called the regulating valves. For these types of valves, the setting is of primary importance. For a flow control valve, this setting refers to the flow setting, and for a throttle control valve, it refers to a minor loss coefficient. For pressure-based controls, however, the setting may be either hydraulic grade (pressure reducing valves (PRVs) and pressure sustaining valves (PSVs)) or the pressure that the valve tries to maintain [6]. Pump control valve, which is a type of flow control valve, is located on the pump outlet and opens gradually on pump start, and closes slowly on pump shut down as a mean of eliminating the risk of pressure transiets (water hammer) occurring on start or stop sequences. Other types of valves are: pressure relief valves to protect the network against excessive pressures; scour valves, used to flush networks of sediment or debris.

2.3.2 Appurtenances

Fire hydrants: Fire hydrants are typically a globe valve in an epoxy-coated cast-iron body. A fire hydrant is designed to stay in their normally closed position for long periods of time, but when required they must reliably open and provide a high flow at a minimum pressure drop.

Pumps: A pump is an element that adds energy to the system in the form of an increased hydraulic head. Since water flows “downhill” (i.e. from higher energy to lower energy), pumps are used to boost the head at desired locations to overcome piping head losses and physical elevation differences. Unless a system is entirely operated by gravity, pumps are an integral part of the distribution system [6].

In water distribution systems, the most frequently used type of pump is the centrifugal pump. A centrifugal pump has a motor that spins a piece within the pump called an impeller. The mechanical energy of the rotating impeller is imparted to the water, resulting in an increase in head [6].

Other appurtencance may include surge tanks (for arresting pressure transients) and water zone metres.

2.4 Pipe Materials

Common materials used in transmission, distribution and reticulation systems and their characteristics are given in the following list [7].

Asbestos cement: Used in distribution networks, asbestos cement pipes are easy to handle, but may damage easily or deteriorate when surrounded by aggressive soils [8].

Cast iron (ductile, cement-lined): These are the most commonly used pipes in distribution mains. They are used in smaller sizes, are strong and easily tapped, but subject to corrosion [8].

Prestressed concrete: These may be used up to very large sizes and are durable, but may deteriorate in some soils [8].

Polyvinyl Chloride (PVC, Modified PVC (MPVC), Un-plasticised PVC (UPVC)): These pipes are commonly used in distribution mains, they are lightweight, easy to install, and resist corrosion. However, care is required when handling [8].

Polyethylene (PE, High density PE (HDPE), Medium density PE (MDPE includes PE80 and PE100)): Suitable for both water and wastewater services, they are durable, corrosion resistant, lightweight and flexible, easy to install, and inexpensive. However, these can only be used for cold water supply [9].

Steel (STL): Used more for transmission lines than distribution lines, steel pipes are found in a wide range of sizes, up to very large. They can be adapted to many conditions but are subject to corrosion [8].

Copper: Used more for domestic water services and distribution networks, copper pipe is durable (i.e. corrosion resistant) and can be recycled [9].

Fibreglass (reinforced fibreglass (RFFG), Glass reinforced plastic (GRP), and glass reinforced epoxy (GRE)): Cheaper than carbon fibre, stronger than many metals by weight, these pipe materials are non-magnetic, non-conductive, transparent to electromagnetic radiation, chemically inert under many circumstances and available in diameters from 100 mm to 4000 mm.

The majority of force mains are metallic pipe, which includes cast iron, ductile iron, and steel pipes. Almost half of metallic force main failures are due to external and internal corrosion, and failures may initiate as a result of surge pressure or joint leakage.

Non-ferrous pipes include prestressed concrete cylinder pipes (PCCP), reinforced concrete cylinder pipes (RCCP) and bar wire wrapped pipes (BWP), and dominate in diameters of pipes above $900\ mm$. Failures of these non-ferrous pipes tend to be more catastrophic, and may occur due to corrosion, structural defects, surge pressure or joint leakage.

2.5 Flow Meters

Flow meters are used on bulk water supply pipes to measure how much water is being used or produced. Regular meter readings give the water supplier a picture of daily, weekly and yearly demand. Monitoring water usage can also help to detect leakage in a network. Also, there is an increasing tendency to install zone meters to improve demand management and to identify and reduce leakage. Meters at the point of take are mandatory in NZ in most cases for takes in excess of 5 l/s under Ministry for the Environment (MFE) Regulation 2010 [10]. Water meters may also be installed at service connections to provide a basis for charging. The meters installed at the property owner’s boundary are called domestic meters, downstream of the stopcock [11].

A number of different flow meters are available for various metering applications. Three types of flow meter are normally used in public water supplies:

- Mechanical flow meters
- Electromagnetic flow meters
- Ultrasonic flow meters

2.6 Pipe Leak Detection

Leakage is the amount of water which escapes from the pipe network by means other than through a controlled action [12].

Classification of Leaks: Leaks can be classified into background and burst related leaks, where bursts represent structural pipe failures and background leaks represent the water escaping through cracks, inadequate joints. [12].

Some water loss through leakage is inevitable in all systems. The leakage is typically from the underground pipework and fittings. Leak detection techniques can be categorised into non-hydraulic and hydraulic techniques.

Further classification of leak detection techniques is based on their nature. An Intrusive Technique is one that involves adding or introducing an external tool into a pipe network for the condition assessment, while Non-Intrusive Techniques are those that do not involve adding or introducing an external tool into the pipe network for condition assessment. Destructive Techniques are those that involve removal of a sample from the pipe network for testing of the sample (based on the assumption that the sample is representative of the remainder of the original pipeline).

Non-hydraulic techniques detect leaks based on external clues such as noise-emission, a point of high electric conductivity (signifying a collection of fluid), non-uniformity in the pipe material, or simply a point in the ground where water appears to be originating. Non-hydraulic methods for pipe leak detection include visual inspection methods, electromagnetic methods, acoustic methods (including leak noise correlation), ultrasound methods, radiographic methods, and robotic PIGs (pipe inspection gauges). These techniques are short-ranged and can detect a leak at close proximity (<250 m) [13].

Hydraulic techniques of leak detection utilise the fact that a leak causes a noticeable change in hydraulic behaviour such as an imbalance between inflow and outflow, change in frictional losses between different sections, or change in the unsteady behaviour of the system. These changes can be detected at large distances from the leak and can be used as a means of wider system monitoring [13].

Hydraulic techniques can be further divided into steady state methods and unsteady state methods. Steady flow occurs when the flow and head conditions at any point do not change with time, whereas in unsteady flow, flow conditions change. Flow in water distribution systems is often unsteady due to fluctuations in demands and boundary conditions. For this reason, unsteady state methods are better suited for water distribution systems. Examples of steady state methods include mass balance and hydraulic grade line measurements, whereas unsteady state leak detection requires the measurement or application and analysis of fluid transients (pressure changes with time). A leak in a pipeline changes the measured pressure response of an injected signal. The nature of such changes provides clues as to the state of a system and can be used as a tool for detecting and locating the leak [13].

Transient flow

Pressures that change with time are known as fluid transients, which are associated with unsteady fluid flow in a pipeline system. If the fluid is water, the phenomenon may be known as the *water hammer effect* [14]. It can also be defined as the intermediate-state flow describing the transition between two steady state flows. Any change or disturbance (whether planned or accidental) can initiate transient conditions. Common boundary conditions that may introduce transients in pipeline systems include sudden changes in pump or valve settings, starting or stopping of pumps and changes in the level of a reservoir [14].

Detection Principle

All transient base methods for the purpose of the pipe fault detection employ the same principle, which is to extract information about the potential pipe or system fault by analysing the measured traces of fluid transient behaviour (the pressure history over time).

Transient generation

The transient signal that is analysed in the test can rely upon natural sources of fluid excitation, generated by an induced event (pipe failure or pipe leak/burst) or artificial events, such as injecting a prescribed transient signal into the pipe flow through valve operation. The subsequent behaviour of the transient event is analysed to acquire the system properties.

Domain type

After the time history of the pressure transient signal is measured by pressure transducers, the analysis of the data can be completed in the time domain or/and frequency domain. The time-domain methods analyse data straightforwardly in the time domain, while the frequency-domain methods require mathematical conversion using fast fourier transforms or another relevant subdivision into time varying components.

Analysis Approach

There are two approaches considered in the transient techniques, namely the *signal processing approach* and *hydraulic transient model simulation*. Signal processing is a method to extract information from measured data and compare it with the data set from a fault-free benchmark on the basis of properties of leak-induced perterbations of a flow or pressure signal [14]. Hydraulic transient models simulate data and reproduce pressure traces in the time or frequency domains. Based on the degree of coincidence between the data from accurately modelled systems with faults and measured data, information related to the fault is determined.

Two detection procedures with different configurations can be developed based on the propagation analysis of the pressure signal. A *signal processing approach* locates the generator and the transducer of the transient at the end of the pipeline, and the *inverse method* using a hydraulic model generates the transients and measures the pressure response at multiple locations along the pipe [14].

In summary, according to the manner in which transient signals are applied, the methods can be divided into four types: the transient reflection method (TRM), the transient damping method (TDM), the system response method (SRM), and the inverse transient method (ITM).

2.7 Factors Influencing Pipe Failures

The failure of a pipe results from the cumulative effect of various pipe-intrinsic (such as pipe material, diameter, joint system, pipe coating and lining, manufacturing defects, and age), operational (such as corrosion, pressure, external stresses) and environmental factors (such as temperature, rainfall, soil conditions). Environmental and pipe-intrinsic factors can be divided into those that are static and those that are dynamic (time-dependent); operational factors are inherently dynamic [15].

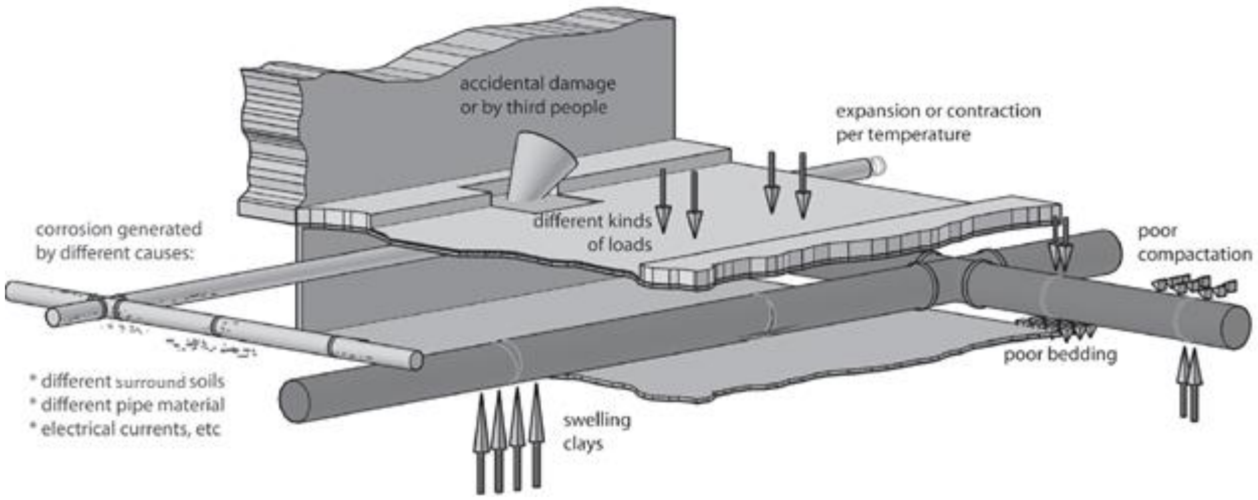

Figure 1: Factors affecting pipe failures. Adapted from Mora-Rodriguez, et al. [16].

2.8 Types of Pipe Failures

Pipe failures occur when environmental and operating tensions put in danger the structural integrity through corrosion, degradation, inadequate installation or manufacturing defects and overstressing due to ground movement [17]. Failure types are associated with the different forces acting on the pipe. Water pipe failure types include:

- **Circumferential break:** A circumferential break (Figure 2 (a)) is generally caused by tensile stresses in the axial direction caused by longitudinal bending or tensile axial forces associated with soil movement or thermal expansion and contraction, and loading (heavy traffic) forces. It covers all breaks that are normal to the pipeline axis, and may be associated with pitting or other defects.
- **Longitudinal split:** Longitudinal cracks (Figure 2 (b)) are often caused by transverse and radial forces (internal water pressure) possibly in conjunction with pre-existing defects acting as a point of weakness [18].
- **Joint failure:** Joint failures (Figure 2 (c)) are typically caused by tensile or compressive forces disturbing the gasket components, but may also result from shear forces or rotations caused by differential ground movements [19].
- **Pinhole leaks:** holes (Figure 2 (d)) are typically caused by radial pressures in conjunction with graphitisation or some other form of corrosion [18]; contrary to the nomenclature, they are generally significantly larger than the diameter of a pin.

(a)

(b)

(c)

(d)

Figure 2: Modes of failure (a) circumferential crack (b) longitudinal crack (c) joint failure, and (d) pinhole leak. Adapted from Barton, et al. [18].

3 Pipe Condition Assessment Techniques

3.1 Non-hydraulic Leak Detection Techniques (commercially available)

3.1.1 Visual Inspection

3.1.1.1 CCTV Pipe Inspection

CCTV pipe inspection technique is used for inspecting water pipelines, pressurised wastewater rising mains and storm water mains.

The Inspector unit can be introduced into a pipe via an existing air valve or similar entry with typically no excavation or pipe-cutting required. Due to the unit's autonomous operation, it can traverse continuous sections of up to $50\ km$ of water mains or rising sewer mains per inspection. In addition to detecting leaks, it can also detect air and gas pockets, record pressure along the full length of the pipe under inspection, and measure turbidity, temperature and conductivity.

The Inspector unit can easily navigate around 90° bends, operates in upto $100\ bar$ pressure environments, includes a high definition (HD) camera for internal inspection, and can be applied to any hard-to-reach pipes such as under highways, at airports or in other access sensitive locations.

Name	CCTV Pipe Inspection
Status	Commercially available (for example: from Detection Services)
Purpose/Scope	Locate leaks, air and gas pockets
Types of pipe it has been used for	For water, wastewater and stormwater pipes
Access to pipeline	Via an existing air valve or similar entry
Source of information	Detection Services[Note 1] http://www.detectionservices.com.au/services/pipeline-condition-assessment/pipe-inspector/
Advantages	• A self-floating and self-levelling device • Material: for any pipe material • Works under traffic noise/fluid turbulence noise: yes • Single pipe or pipe network: pipe network • Features/faults/pipe wall deterioration: air and gas pockets and leak detection • Works on a live network: yes • Range of pipelines on which this technique has been used: for any water, wastewater and sewer water (diameter range from $150\ mm$ – $3000\ mm$) • Frequency of reassessment: periodic reassessment/time based maintenance • Identified leaks: high sensitivity leak detection to the smallest leaks • No pre-cleaning of pipelines is required • Require specific skills/operator: yes • Can survey long pipelines with a single deployment. The total length of survey capacity depends on the flow rates in the pipeline and battery life. The longest water line survey presently is $50\ km$.

	• Records visual details such as installation fittings, connectors, peaks, low points and damage • Provides continuous data from inside a pipeline • An optical HD camera provides visual and audible signals of images for recording and analysing
Limitations	Intrusive technique Operates in up to $100\ bar$ pressure environments
Performance	No information available
Breadth of use	**Available to be used in NZ**

Note 1. The information provided in this report for this and the other technoloogies described in Section 3 has been obtained from the specialist contractor offering the service, and has not been independently verified.

3.1.2 Acoustic Methods

3.1.2.1 Free-Swimming Leak Detection Device

Free-swimming leak detection devices are used for the assessment of pressurised water and wastewater pipelines of $200\ mm$ diameter and larger. The tool is equipped with a highly sensitive acoustic sensor, accelerometer, gyroscope, magnetometer, ultrasonic transmitter, and temperature sensors. This acoustic sensor can detect small (pinhole sized), medium and larger leaks and air pockets. This device travels with the water flow down a pipe and detects, locates and estimates the magnitude of leaks as it rolls. Attached accelerometer and gyroscope measure the movement of the device that can be used later for mapping. The magnetometer measures the magnetic field coming up from the pipelines, which can be used to find joints and other features related to the pipeline. All these are encased in an aluminium alloy core with a power source and other electric components [20, 21]. 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 otherwise generate while traversing the pipeline [22]. The diameter of the outer sphere depends on the pipe diameter and flow conditions.

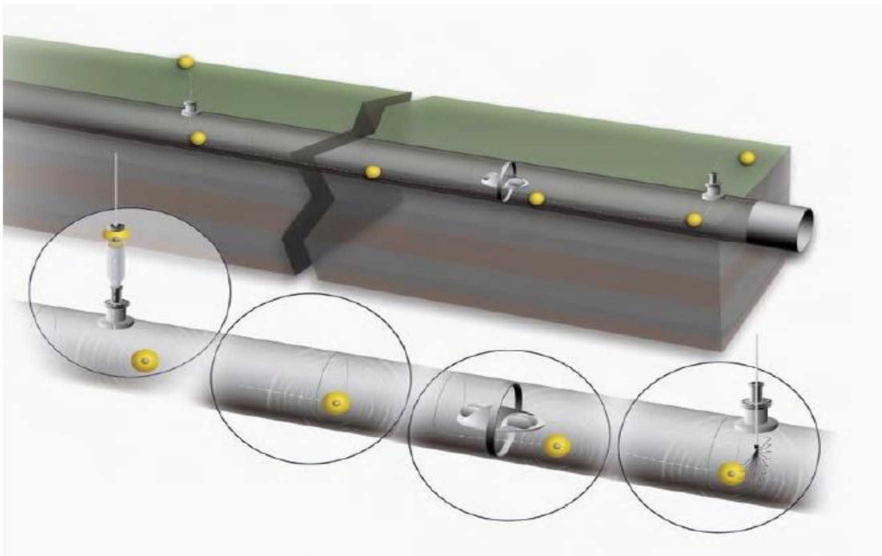

Figure 3: Free-swimming leak detection device for the assessment of leaks and air pockets in pressurised water and wastewater pipes. Adapted from Ellison [23].

The device is deployed into the water flow of a pipeline and captured downstream. Special nets are used for the standard extraction of the device and to remove it from all pressurised, in-service pipelines. The device continuously records acoustic data and emits an acoustic pulse for tracking purposes, while the device traverses the pipeline. The recorded acoustic data are analysed to identify air pockets and leaks. 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 [22].

Another strength of this free-swimming leak detection device is that there may be many alternative options available to insert it into and extract it from pipelines. Having multiple options reduces costs to utilities for support of the inspection [21].

This device has been used for condition assessment, and for reducing non-revenue water [21]. From a condition assessment perspective, this device can be a part of a larger holistic approach to help identify problems that can be repaired before they become bigger issues, and to prioritise capital spending. On the non-revenue water side, because the acoustic sensor traverses directly past the leaks, it can inspect transmission mains with a greater level of accuracy than traditional methods.

Figure 4: Deployment of a free-swimming leak detection device into the water flow of a pipeline. Adapted from PureTechnologies [21].

Name	Free-swimming leak detection device
Status	Commercially available (for example: from Pure Technologies)
Purpose/Scope	Locate leaks, air pockets, visible defects and support condition assessment
Types of pipe it has been used for	Water and Wastewater pipes (for medium and large diameter pipes, i.e. those $\geq 200\ mm$)
Access to pipeline	Insertion and extraction points, valve, hot tap connection
Source of information	Pure Technologies ([21], https://puretechltd.com/technology/smartball-leak-detection/
Advantages	• Material: can be used for any pipe material (Concrete, Steel, PVC, Glass-fibre reinforced polyester, etc.) • Works under traffic noise/fluid turbulence noise: yes • Features/faults/pipe wall deterioration: air pockets and leak detection and condition assessment • Works on live network: yes

	• Range of pipelines on which this technique has been used: pipe diameter $\geq 200\ mm$ • Frequency of reassessment: periodic reassessment/time based maintenance • Identified leaks: All minor and major leaks • Long pipelines can be assessed with a single deployment. The total length of an individual survey depends on the flow rates in the pipeline and battery life. The longest water line survey presently is $15\ miles\ (25\ km)$ under $0.6\ m/s$ flow. • Can detect very small noise disturbances along the pipeline. • In one previous inspection, 2,000 leaks were found in 1,000 miles (1,600 km)
Limitations	• Intrusive technique • Cannot be used for pipelines with very high pressure $(> 400\ pounds/sq.in.)$ • If the survey involves long pipe lengths, the surface sensor used for monitoring the pulse being emitted from SmartBall has to be moved along the pipe length [24].
Performance	• Location accuracy depends on how well the configuration of a pipeline is known. Typically, the location accuracy of the device is within $3\ ft\ (1\ m)$[24].
Breadth of use	• It has been used in many countries, including the U.S., Canada, and Mexico, on a wide range of pipe materials [24]. **This is not currently available in NZ.**

3.1.2.2 Tethered Leak Detection Tool

Tethered leak detection tool is an inline tool that can assess pipelines $100\ mm$ and larger because it is tethered and an operator has complete control. This tool uses a hydrophone tethered to an umbilical cable, which travels inside in-service water mains, to record leak noises [22]. The tool can be stopped and reversed to investigate the events of interest such as leaks, air pockets, and visual anomalies. The tool can travel with the product flow velocity from as little as 0.3 metre/second up to 3 metre/second with no disruption to the service [21].

To insert the tool into an active pipeline, almost any existing 50 mm tap or greater can be used, usually requiring only minor modifications. During the insertion setup, the equipment is disinfected and the product flow velocity is measured and the tool insertion setup tube is mounted, into which the probe is loaded. The probe is hand inserted into the pipe as progress is monitored on the video, and for the duration of the inspection, the cable is continuously disinfected as it leaves the spooler [21]. As the tool enters the pipe, a small parachute is inflated by the flow velocity of the water and the parachute pulls the tool through the pipe with its on-board LED lighting system highlighting any visual defects in the pipeline.

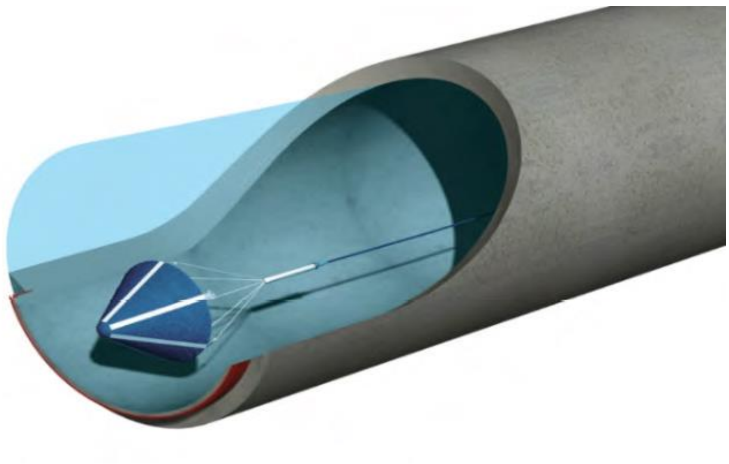

Figure 5: Tethered leak detection tool. Adopted from Ellison [23].

If the leak detection tool encounters any acoustic events such as a leak, the operator can stop the tool and pinpoint the probe on the leak. At the same time, the above-ground operator locates the probe above ground, establishing the exact leak location within $\pm 450\ mm$. This enables the user to locate leaks in real time and decide where to excavate. The tool can detect multiple types of leaks and air pockets in the pipeline both visually and acoustically [21]. The tool can navigate horizontal and vertical bends without difficulty, up to 270° of cumulative bends or greater in a single inspection.

Wastewater force mains have also been successfully inspected by flushing the line with clean water during the inspection [22].

Name	Tethered leak detection tool
Status	Commercially available
Purpose/Scope	Locate leaks, air pockets, visible defects and wall thickness
Types of pipe it has been used for	Water mains (can be used for small mains ($100\ mm$) and equally effective in large diameter mains because of the proximity of the sensor to the leak [24]).
Access to pipeline	Via any existing 50 mm inch tap or greater
Source of information	https://puretechltd.com/technology/sahara-leak-gas-pocket-detection/ https://www.wateronline.com/doc/sahara-pipeline-inspection-system-0001
Advantages	• Material : All materials • Features/faults/pipe wall deterioration: leaks and pipe wall deterioration • Works on live network: yes • Range of pipelines on which this technique has been used: $\geq 100\ mm$ • Frequency of reassessment: Periodic reassessment • Identified leaks: Sensitive to small leaks • Surface tracking can map the pipeline under inspection [24]. • Tether control allows withdrawal of the sensor when unexpected flow conditions are encountered. It also allows extending the listening period at a particular location, if needed [24]. • Use existing $50\ mm$ taps

	• Handles pressures up to 200 psi (14 Bar)
Limitations	• Intrusive technique • Requires access points at a frequency that is determined by bends and flow rates in the pipeline [24].
Performance	• Buried unknown leaks as small as $\frac{0.25gal}{hr}$ or $\frac{0.005gal}{min}$ have been successfully located • The accuracy of leak location is generally less than $1000\ mm$
Breadth of use	It has been used in the U.S. since 2007. **This is not currently available in NZ.**

3.1.2.3 Leak Noise Correlation (Technique 1)

Leak Noise Correlation system is used for locating leaks in water distribution and transmission pipes using the cross-correlation method [25]. The 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 a fire hydrant [22]. Accelerometers are used to sense the 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[25]. The computer calculates the cross-correlation function of the two leak signals to determine the time lag between the two sensors. Propagation velocity needs to be determined experimentally or is estimated based on the type and size of the pipe.

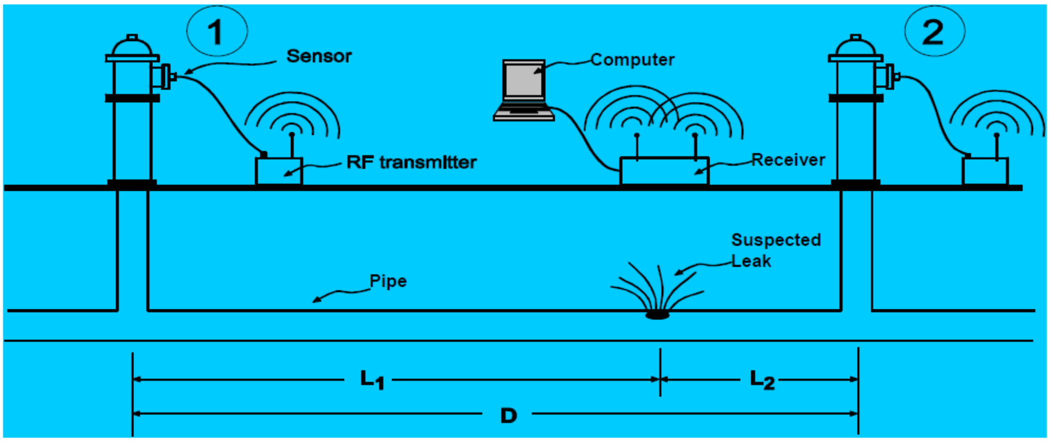

Figure 6: The principle of leak noise correlation technique for leak detection. Adopted from Hunaidi, et al. [25].

Name	Leak Noise Correlation (Technique - 1)
Status	Commercially available
Purpose/Scope	Locate leaks.
Types of pipe it has been used for	Water (Distribution main and transmission main)
Access to pipeline	Via fire hydrant
Source of information	Hunaidi, et al. [25] https://www.echologics.com/products/leakfinderst/ https://www.hydrograph.com.au/water-products/acoustic-leak-detection/leak-noise-correlator/

Advantages	• Material: All types of pipes including PVC and PCCP, Steel, Ductile Iron, Cast Iron, Asbestos Cement, Concrete, Copper, Glass Reinforced Plastic, HDPE, MDPE, and Lead • Diameters from ½" to 16". • Works under traffic noise/fluid turbulence: Yes • Works on live network/drainage require: Works on live network • Frequency of reassessment: Periodic reassessment • Identified leaks: All minor and major leaks (this system can find leaks as low as 63 millilitres per second if longer recording times are used) • Non-Intrusive technique (sensors placed on hydrants, valves etc.) • Uses a low-frequency vibration sensor to locate leaks in plastic pipes.
Limitations	• Information about the leak size is not available from the test [24] • Sensor spacing is influenced by both the pipe diameter and the pipe material due to attenuation of the acoustic signal. • May be susceptible to interference from low frequency vibration (e.g. pumps and road traffic) [24] • For condition assessment, results from the inspection will be at a segment level (the technology measures wall thickness for the entire segment length, typically around 100 m). • Current assessments do not provide information on tuberculation, but developments are underway to add that capability [26].
Performance	Performance of the LeakFinderST system has been tested for [24]: • Narrow-band leak noise in PVC pipes • The monitoring duration depends on the quality of the signal • Longer monitoring times reveal less noisy leaks, or when there is significant noise.
Breadth of use	It has been used commercially in **Australia (kits have been sold in Australia)**, the U.K. and **NZ.**

The advanced signal processing approach provides improved resolution for narrow-band leak signals. This is helpful for plastic pipes (low frequency sound emission), small leaks, multiple leaks and for settings where leak sensors are closely spaced, and situations with high background noise. Enhanced function also does not require the usual filtering of leak signals to remove interfering noise [25].

Signals from leak sensors can be transmitted wirelessly to a computer for processing. Leak sound is recorded and correlated by the correlator in a few minutes under most circumstances, but noisy records can take longer to process. The cross-correlation results are displayed on the screen and continuously updated in real time while leak signals are being recorded [22].

Based on principles similar to leak noise correlation, a technique, W*all Thickness Finder* was developed to estimate the average pipe wall thickness between two listening points on the pipe [27]. 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 moduli of the pipe wall and the water [27]. Velocity measurement can be performed with the same hardware as LeakfinderST by using the cross-correlation method [22].

3.1.2.4 Leak Noise Correlation (Technique 2)

This correlator technique finds leaks on a variety of pipe materials and large diameter mains (diameter range of $100\, mm\ to\ 300\, mm$) [28]. The sensors are built into a standard fire hydrant cap and are capable of identifying extremely faint acoustic noise emitted by leaks before they become detectable by conventional methods. The correlator system utilises a series of smart fire hydrant caps (fitted to above ground hydrants typical in the U.S.A.) equipped with built-in acoustic sensor, processor, and communication components. At the heart of the platform is an intelligent node which is embedded into the standard fire hydrant cap. The platform is designed to provide more accurate information on the location of a leak. The smart node listens for and correlates any noise throughout the network on a daily basis and reports each point of interest to an application user interface for viewing by a utility operator. The node is installed using common tools at a tablet application which enables a technician to connect the node to the monitoring network [28].

Installation of nodes into fire hydrants offers several benefits that improve system performance and extend equipment life. The above-ground location of the node antenna enables a stronger and more stable radio signal. Placing the node in a hydrant cap also offers a better protected installation environment compared to valve box installations that can suffer from salt, silt, and dirt accumulation [28].

Name	Leak Noise correlator (Technique – 2)
Status	Commercially available
Purpose/Scope	For leak detection on water distribution main pipelines of diameter from $100\, mm\ to\ 300\, mm$
Types of pipe it has been used for	Water distribution mains
Source of information	https://www.echologics.com/services/small-diameter-leak-monitoring/echoshore-dx/
Advantages	• Material: All material types including steel, cast iron, and ductile iron • Works under traffic noise and fluid turbulence • Can work on pipe networks • Can find any types of leaks • It works on a live network • Access to pipe via fire hydrants • Range of pipelines on which this technique has been used : diameters from $100\, mm\ to\ 300\, mm$ • Frequency of reassessment: continuous monitoring/condition based maintenance • Identifies total leaks
Limitations	There are limitations related to installation, with a requirement to customize the site to install the TX nodes. Traffic control, access to chambers, drilling, antenna installation all need to be considered. For condition assessment, results from the inspection will be at a segment level (the technology measures wall thickness for the entire segment length, typically around 100 m).
Performance	Specifications indicate it can detect leaks of 315 millilitres per second or higher, though smaller leaks have also been located.

Breadth of use	It has been used commercially in the U.S.A. and Canada and is also available in France. **This is not available currently in NZ or other countries.**

3.1.2.5 Leak Noise Correlation (Technique 3)

This correlator technique is designed to monitor critical and high risk water transmission mains [28]. The monitoring platform combines proven acoustic leak detection technology with leading-edge wireless connectivity and visual end-user dashboards to create a cost-effective monitoring solution. The correlator can be applied throughout the transmission system on any pipe material with a diameter of $400\ mm$ or larger. At the heart of the platform is a node, which is typically installed underground, in an access chamber or any other locations with secure access to the main. A node is self-contained and consists of a data processor, communication hardware, battery power source, hydrophone and a durable antenna [28].

Node installations are quick and simple as key components are secured to the chamber wall and a hydrophone is connected to a new or existing access port, such as an air release valve. Nodes are added in the same manner over the desired distance of the transmission main to be monitored [28]. The platform is able to monitor short or long distances on a permanent or temporary base. The correlator can be deployed non-intrusively with no interruption to operations. Once activated, the system collects data above the transmission main. At pre-determined times the platform uploads data to the secure server, where advanced algorithms are applied to interpret the information. Data is transmitted to the server using a cellular network or through satellite communications in remote locations [28].

In the event of a leak, the correlator node captures data and send it to the central server for signal processing and leak location identification. This information allows operators to act quickly before a small problem becomes a major issue [28]. Several parameters such as static pressure, flow rate, temperature, chlorine levels, acoustic anomalies, and other operator requirements can be monitored at the same time [28].

Name	Leak noise correlation (Technique – 3)
Status	Commercially available
Purpose/Scope	For leak detection in all transmission main pipelines of size $> 400\ mm$
Types of pipe it has been used for	Water transmission mains
Source of information	https://www.echologics.com/services/large-diameter-leak-detection/echoshore-tx/
Advantages	• Material: All material types including pre-stressed concrete, steel, cast iron, ductile iron and plastic pipe • Works under traffic noise and fluid turbulence • Works on pipe network • Detects pipe leaks • Works on live network • Range of pipelines on which this technique has been used : All transmission main pipelines of size $> 400\ mm$ • Frequency of reassessment: continuous monitoring/condition based maintenance • Identifies all major and minor leaks • Access to pipe via existing chamber, purpose-built access, above-ground utility box, and direct-to-pipe

Limitations	No information available
Performance	Specifications indicate it can detect leaks of 5 gallons per minute or higher, though smaller leaks have also been located.
Breadth of use	It has been used commercially in the U.S.A., Canada and Singapore. **This is not currently available in NZ.**

3.1.2.6 Pipeline Condition Assessment Technique

Pipeline condition assessment technique can identify the condition of both distribution mains and transmission mains, while simultaneously searching for leaks, all without the need for large excavations or service disruptions [28]. This technology does not require access to the inside of a pipe or extensive support from utility field crews for either inspection or data collection. It can work on distribution main pipe diameters (range: $100\ mm\ to\ 300\ mm$) and transmission main pipe with diameters (range: $400\ mm\ to\ 2200\ mm$) Supported pipe materials include asbestos cement (AC), cast iron, ductile iron, steel, and mortar lined, pre-stressed concrete cylinder pipe (PCCP).

For field inspection, the equipment is portable and consists of a laptop computer to capture and analyse data, a transmitter that is typically placed on the roof of a vehicle to capture signals from two receivers at either end of the pipe section that is being inspected. The receivers are connected to the water main using magnetic acoustic sensors [28].

In this technology, acoustic sensors are attached to existing contact points on distribution mains, such as fire hydrants, operating nuts of valves or via direct access to the pipes. For a transmission main, the attachment points can be a release valve or through direct access to the pipe obtained via excavation [28]. A sound wave is induced that travels along the pipeline. The acoustic sensors capture the time it takes the sound wave to travel between two sensor stations. The speed at which the sound wave travels is dictated by the condition of the pipe wall [28]. As a sound wave travels, it pushes water molecules towards each other. Because water is incompressible, the molecules push outward on the pipe wall. This places a microscopic flex on the pipe wall, with greater responses indicating low stiffness pipe. Through this method, Epulse measures the stiffness of the pipe wall which is an ideal measure of actual pipe condition [28].

Once the acoustic data is captured, engineers use patented algorithms to convert the data into a measure of the average minimum remaining wall thickness of the inspected pipe segment. For metallic and AC pipe, the calculated wall thickness measurement is compared to the original thickness of the pipe to determine the average percentage of wall loss.

This inspections have virtually no impact on local traffic, businesses or the daily activities of residents [28].

Name	Pipeline condition assessment technique
Status	Commercially available
Purpose/Scope	For condition assessment and finding leaks from transmission and distribution mains
Types of pipe it has been used for	Water transmission and distribution mains
Source of information	https://www.echologics.com/services/condition-assessment/epulse/
Advantages	• Material: Metallic, asbestos cement, cast iron, ductile iron, steel and mortar lined, and pre-stressed concrete

	• Works under traffic noise and fluid turbulence • Works on the pipe network • Used for finding leaks, and condition assessment of pipes • Works on the live network • Range of pipelines on which this technique has been used: Distribution mains (range from $100\ mm\ to\ 300\ mm$) and transmission mains: (range from $400\ mm\ to\ 2200\ mm$) • Detects all minor and major leaks • Access to the pipe via fire hydrants, valves or through a direct contact
Limitations	Assessments may not be able to pass sections that have been repaired
Performance	No information available
Breadth of use	It has been used commercially in the U.S.A and Canada. **This is not currently available in NZ.**

Factors influencing effectiveness of acoustic methods

The effectiveness of acoustic leak detection methods depends on several factors including pipe size, type and depth, leak type and size, system pressure, interfering noise, and the sensitivity and frequency range of the equipment [29]. The pipe material and diameter have a significant effect on the attenuation of leak signals along the pipe. For example, leak signals travel farthest in metal pipes and are attenuated greatly in plastic ones. The larger the diameter of the pipe the greater the attenuation, and the harder it is to detect the leak. The pipe diameter and material also affect the predominant frequencies of leak signals - the larger the diameter and the less rigid the pipe material, the lower the predominant frequencies. This effect makes leak signals susceptible to interference from low-frequency vibrations, e.g., from pumps and road traffic [29].

There is significant variation in the sensitivity, frequency range, and signal-conditioning and processing features of different acoustic leak detection devices. The more sensitive the leak sensors and the higher the signal-to-noise ratio of the equipment, the smaller the leaks that can be detected. Modern acoustic devices incorporate signal-conditioning components such as filters and amplifiers to make leak signals stand out. The filter removes interfering noise occurring outside the predominant frequency range of the leak signals. Amplifiers improve the signal-to-noise ratio and make weak signals audible [29].

3.1.3 Electromagnetic Methods

Electromagnetic inspection has been considered as an effective condition assessment method for prestressed concrete cylinder pipes (PCCP). The following electromagnetic techniques can perform the inspection without service shutdown, or with minimal operational downtime.

3.1.3.1 Free-Swimming Tool

Free-swimming tools are specially designed to operate in live pipelines and can collect data regarding the condition of the pipe wall. This tool can be used for water and wastewater pipelines and are available in three diameter ranges. The Mini swimming tool is suitable for pipelines in a diameter range from $40\ to\ 1200\ mm$. The small size tools are suitable for pipelines with a diameter range of $600\ to\ 1800\ mm$, whereas, large size tools are available for pipes with a diameter range of $1200 - 3000\ mm$ [30]. These tools are useful for assessment of the structural condition. These tools are designed to inspect prestressed concrete cylinder pipes (PCCP) and metallic pipes such as ductile iron and steel. A typical inspection using this technique lasts for about a day. A single mobilisation of this tool can inspect pipeline distance ranging from $5\ to\ 8\ km$.

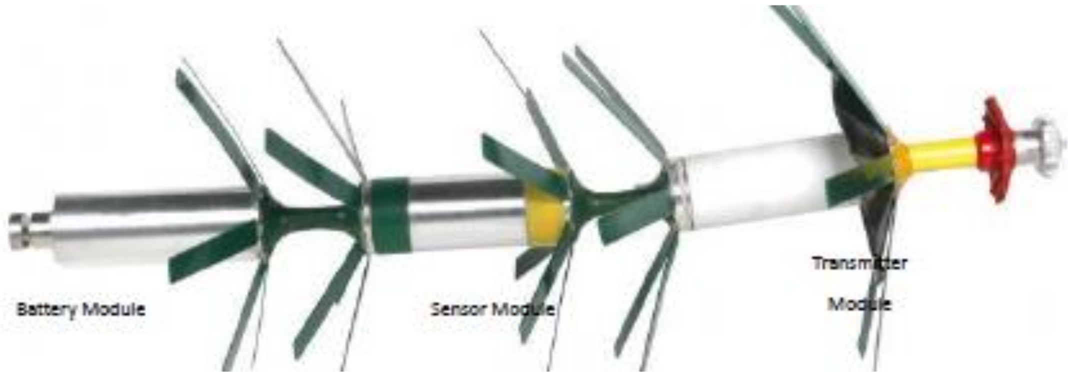

Figure 7: Free-swimming tool for a small diameter pipe. Adopted from [Wang, et al. [31]]

The free-swimming tool consists of navigation aid, battery module, electromagnetic (EM) module, tracking module, and sensor module, as shown in Figure 7. It can be inserted into the pipeline via a chamber, open channel or small hot tap [30]. As the tool enters the pipeline, it uses buoyancy and its fins to quickly stabilise itself in the centre of the pipe. The tool travels at virtually the same speed as the flow velocity in the pipeline [31]. With its flexible design, the tool can travel through a variety of bends in the pipeline, including 45 and 90 degree turns. It can also navigate through, tees and butterfly valves which must remain open during inspections [30]. The detectors that are positioned in around the tools pedals and on the body of the tool enable it to collect data and identify where the problems in the pipe wall occur. The free-swimming tools are also equipped with cameras to collect video data in the pipe, which provides an additional layer of condition assessment data. The tool can be extracted through pressurised connections, via a guide web and robotic grapple from the pipeline. It can also be extracted from a reservoir.

Name	Free-swimming tool
Purpose/Scope	Inspects PCCP and metallic pipes, can operate in a live pipeline, and is available in a wide range of pipe diameters.
Access to pipeline	Via Chamber, open channel or small hot tap
Types of pipe it has been used for	Water (Main/transmission), Wastewater
Status	Commercially available
Source of information	PureTechnologies [30], Wang, et al. [31], https://puretechltd.com/technology/pipediver-condition-assessment/

Advantages	• Pipe materials: PCCP and metallic (Ductile iron and steel) • Features/faults/pipe wall deterioration: Can detect broken wire wraps, sedimentation,corrosion, and other anomalies. Data assists in judgments of remaining strength or service life • Works on live network/drainage required: Works on live network • Range of pipelines on which this technique has been used: $400 - 3000\ mm$ • Works for long inspection distances • Frequency of reassessment: Periodic reassessment
Limitations	Data interpretation needs experience and skill. Remaining service life assessments require additional verification and improvement.
Performance	No information available
Breadth of use	It has been used for condition assessment of many PCCP lines in Canada (where the technology was invented) and the USA. **This is not currently available in NZ.**

3.1.3.2 Remote Field Testing

Remote field testing technology involves the generation of electric and magnetic fields to investigate the condition of cast iron material pipes. A remote field testing system consists of an exciting coil and one or more detectors [22]. The exciting coil is driven by a low-frequency alternating current signal. The interaction region is divided into three zones as shown in Figure 8.

- Direct couple zone: magnetic field from the exciting coil interacts with the pipe wall to produce a concentrated filed of eddy current.
- Transition zone: there is an 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.

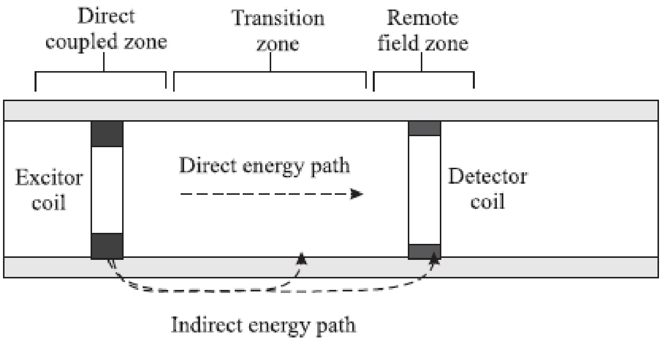

Figure 8: The principle of remote field testing. Adopted from Liu and Kleiner [22].

Two distinct coupling paths exist between the exciter and detectors. The direct electromagnetic field inside the pipe is attenuated rapidly by circumferential eddy currents induced in the conducting pipe wall [32]. 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 [22]. 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 with the pipe wall [22].

Name	Remote Field Testing
Purpose/Scope	Inspect cast iron and PCCP pipes as well as ferromagnetic components of composite pipes [32]
Types of pipe it has been used for	Water and Wastewater pipelines
Access to pipeline	Via chamber, open channel or small hot tap
Status	Commercially available
Source of information	Mergelas and Kong [32], Liu and Kleiner [22] https://puretechltd.com/technology/pipediver-condition-assessment/ https://www.wrc-infrastructure.co.uk/technologies/pipediver%C2%AE/ https://www.russelltech.com/News/PID/719/ev/1/TagID/7/TagName/See-Snake
Advantages	• Material: Metallic pipes PCCP, cast iron and the ferromagnetic component of composite pipes • Features/faults/pipe wall deterioration: Can detect broken wire wraps, sedimentation, corrosion, and other anomalies. Data helps support judgments of remaining strength or service life • Works on live network/drainage required: Works on live network • Range of pipelines on which this technique has been used: $50\ mm - 3000\ mm$ • Long inspection distances • Frequency of reassessment: Periodic reassessment
Limitations	Data interpretation needs experience and skill.
Performance	There is a proven ability to identify prestressed wire breaks, but very limited data exists connecting wire breaks to loss of pipe stability or remaining service life.
Breadth of use	It has been used widely in Canada (where the technology was developed), the U.K. , the U.S.A., and the Netherlands. **This is not currently available in NZ.**

3.1.3.3 Pipe Penetrating Radar (PPR)

PPR is the in-pipe application of ground penetrating radar (GPR). GPR is used to investigate the subsurface of the earth by emitting electromagnetic waves and measuring the reflected signals. PPR is the adaptation of this technology from inside pipes. PPR can be used to detect pipe wall fractures, changes in material, reinforcing location and placement, and pipe wall thickness. PPR may also detect the presence of voids developing outside the pipe. PPR survey can be conducted via manned entry or with remotely operated vehicles (ROVs).

Electromagnetic waves have two important properties: they travel at different speeds through different materials, and the amplitude of their reflection is greater depending on the contrast between two materials. By measuring the two-way travel time and the amplitude of the reflected EM waves, a detailed image of the subsurface can be built. By repeating this process continuously along a survey line, a profile of the line can be created. This can be done at multiple clock positions to provide a detailed report on the pipe's current condition, as well as the presence or absence of voids outside the pipe wall [33] .

Name	Pipe Penetrating Radar (PPR)
Purpose/Scope	Mainly used for wastewater pipes with diameter $200\ mm - 450\ mm$
Types of pipe it has been used for	Water and Wastewater pipelines
Access to pipeline	Via manned entry or with remotely operated vehicles (ROVs).
Status	Commercially available SewerVUETechnology [33]

Source of information	https://sewervue.com/pipelines2017-presentation-ppr.html
Advantages	• Material: All non-ferrous pipes (e.g. reinforced concrete, vitrified clay, asbestos cement, PVC, High density polyethylene (HDPE)) • Features/faults/pipe wall deterioration: may detect pipe wall fractures, wall thickness, delamination, voids etc. • Works on live network/drainage required: Works in live network • Range of pipelines on which this technique has been used: $200\ mm - 450\ mm$ • Frequency of reassessment: Periodic reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	There is a need for scientific studies examining performance in circumstances where conditions are known from another soruce. Surface GPR work has been found to be unreliable, though may be effective at tracking changes in condition between scans.
Breadth of use	It has been used in the U.S.A. and Canada. **This is not currently available in NZ.**

3.1.4 Fibre Optics Sensing Techniques

3.1.4.1 Integrated Smart Monitoring Technique (Identified Commercial Technique)

The fibre optic sensing leakage detection method involves the installation of a fibre optic cable to measure the temperature over the entire pipeline length. Conventionally, leakage from pipelines introduces local temperature anomalies in the vicinity of the pipeline [31]. By scanning the entire length of the fibre in short intervals, the temperature profile along the fibre is obtained and the leakage point can be detected. This method provides accurate leakage detection and location [31]. However, the cost of implementing such a system is quite high, especially for a long-range pipeline.

Atlantis Hydrotec***** is a pipe-in-a-pipe solution in which a special purpose, small-bore or a messenger pipe (which is designed to fully isolate the cable from the water) is inserted into existing water pipelines for the purpose of installing ultra-fast fibre optic communication cables [34]. Installation of Atlantis Hydrotec is trenchless so it is rapid, and can be achieved with a minimum of civil works and associated disruption.

Integrated smart monitoring (ISM) technique uses a sensing cable inserted within an Atlantis Hydrotec installation. This sensor has the ability to identify leaks, along the pipe infrastructure and identify the location of the event to within a few metres [34].

The data is captured and monitored via an ISM Analyser unit, which can monitor up to $40\ km$ of pipeline. Multiple analyser units can be networked to allow the monitoring of $1{,}000s\ of\ kilometers$ of pipes from a single location [34].

Name	Integrated Smart Monitoring (ISM)
Purpose/Scope	Mainly used for water transmission and distribution mains for leak detection
Types of pipe it has been used for	Water pipelines (distribution and transmission mains)

Access to pipeline	Via inserted messenger pipe (designed to fully isolate the cable from the water)
Status	Commercially available (from Craley Group)
Source of information	https://www.craley.com/aiguees-vic-choose-ism-for-leak-det
Advantages	• Material: All material types • Access to the pipeline via a specially installed messenger pipe called Atlantis Hydrotec • Works under traffic noise/fluid turbulence: yes • Single pipe/pipe network : pipe network • Features/faults/pipe wall deterioration: leak detection • Works in live network • Range of pipelines on which this technique has been used: All types of water distribution and transmission main • Long inspection distances: up to $40\ km$ of pipeline • Frequency of reassessment: Continuous reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	Not available
Breadth of use	ISM has been commercially used in Spain. **This is not currently available in NZ.**

* The name of the supplier provided here as an example.

3.1.5 Sensor Techniques

The use of a sensor for continuous monitoring is relevant to the concept of structural health monitoring (SHM), which is defined as a process to implement a damage identification strategy for varied infrastructures [35]. The SHM process involves the observation of a network over time with periodical measurements, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system health [35]. Sensor monitoring data are used for condition assessment and estimated deterioration rate for pipes, and eventually contribute to the prediction of residual useful life leading to actionable decision.

Currently, network maintenance is carried out in a time-based mode. The time-based maintenance philosophy is now evolving to a more cost effective condition based maintenance (CBM) philosophy [35]. Sensor technologies play an important role in CBM. There are many sensor techniques available for monitoring water pipe condition. However, many techniques are limited to specific pipe materials. Identified commericially available sensor techniques are as follows:

3.1.5.1 inSCAN

Sensor technique inSCAN is used to detect leaks and pipe condition for large diameter pipes [36]. The inSCAN unit operates on a tether that enters into the water and wastewater mains through a $50\ mm$ or larger tapping or valve under normal system operation and pressure, and with no disruption to the service. The inSCAN sensor is carried with the flow of water, testing the integrity (leaks) in the pipeline [36].

The resulting data gathered from inSCAN allows for the detection of the smallest leaks in all mains diameters ($\geq 300\ mm$) as well as in all pipe materials. It is a fully computerised and SCADA controlled system.

Name	inSCAN
Purpose/Scope	For leak detection and pipe condition assessment
Types of pipe it has been used for	Water transmission (mainly trunk mains) and wastewater
Access to pipeline	via $50\ mm$ or larger tapping or valve
Status	Commercially available (Detection Services)
Source of information	http://www.detectionservices.com.au/services/pipeline-condition-assessment/inscan/
Advantages	• Material: all types • Works under traffic noise/fluid turbulence: Yes • Single pipe/pipe network: Pipe network • Features/faults/pipe wall deterioration: all type of leaks, air pockets, blockages, debris, and condition assessment • Works in the live network • Range of pipelines on which this technique has been used: Mainly trunk mains and wastewater pipes ($\geq 300\ mm$) • Long inspection distances: up to $14\ \mathrm{km}$ of pipeline • Frequency of reassessment: Periodic reassessment • Require skills/operator: Yes
Limitations	• Data interpretation needs experience and skill • Detect leaks in low pressure mains
Performance	Not available
Breadth of use	**This is available in NZ.**

3.1.5.2 P-CAT

P-CAT is a non-invasive, non-destructive technology for performing pipe condition assessment, while the system is in operation [37]. P-CAT can determine remaining thickness of pipe wall to $0.2\ mm$ accuracy over long sections (many kilometres) of pipeline as well as detect and locate defects such as deterioration, pipe material changes, cement material changes, cement matrix loss from AC pipes, blockages, air and gas pockets. P-CAT can be applied on any pressurised fluid filed pipeline carrying potable or drinking, raw or wastewater. P-CAT is most suitable for long distance trunk mains and can be applied to all metallic, concrete and AC pipes [37].

P-CAT equipment includes a pressure transducer, a data acquisition box and a transient generator. A number of sensors are installed on existing pipe fittings- primarily via air valves along a section of pipe. One of the sensors is also used as a generating station. From this point a pressure wave is injected into the pipeline. As the wave travels through the pipeline, it is partially reflected when it encounters any change in pipeline structure, including both known features of the system as well as other issues related to the pipe deterioration [37].

Name	P-CAT
Purpose/Scope	Pipe condition assessment
Types of pipe it has been used for	Water transmission (mainly trunk mains) and wastewater
Access to pipeline	via air valves
Status	Commercially available [37]

Source of information	http://www.detectionservices.com.au/services/pipeline-condition-assessment/p-cat/
Advantages	• Material: all metallic, concrete and AC pipes • Works under traffic noise/fluid turbulence: Yes • Single pipe/pipe network: Pipe network • Features/faults/pipe wall deterioration: can detect deterioration, pipe material changes, cement material changes, cement matrix loss from AC pipes, blockages, air and gas pockets • Can determine remaining thickness of pipe wall to $0.2\ mm$ accuracy over long sections (many kilometres) of pipeline • Works on live network/drainage required: Works in live network • Range of pipelines on which this technique has been used: Mainly trunk mains and wastewater pipes ($400\ mm$ or higher) • Long inspection distances: up to $14\ \mathrm{km}$ of pipeline • Frequency of reassessment: Periodic reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	Not available
Breadth of use	**It has been used in Australia and New Zealand**

3.1.5.3 Multisensor Inspection (MSI) System

The MSI system can detect defects and cavities from non-ferrous pipes of all shapes and sizes. The MSI system consists of Light Detection and Ranging (LIDAR), sonar, CCTV, and pipe penetrating radar (PPR) [38].

Sonar involves the use of sound waves to create an image of the pipe's inner surface below the flow line. Used in conjunction with LIDAR imaging, sonar can generate a 360° image of the pipe that includes quantitative determination of ovality, wall loss, sediment volume, and depth, even through tight bends [39].

LIDAR involves projecting a ring of light onto the pipe's interior wall. This ring of light is imaged using a specially calibrated digital camera. LIDAR surveys are done by projecting a laser, and measuring the time it takes to reach a target and reflect back to the sensor. A LIDAR survey collects continuous $2-$dimensional cross sections of the pipe wall. By compiling these cross sections, a high resolution $3-$dimensional model can be created. LIDAR is used to measure the pipe above the flow line. It collects highly detailed information about ovality, deformations, offset joints, and lateral size. One drawback of LIDAR is that the projected ring of light must be perpendicular to the pipe wall for accurate results [38].

CCTV is used in this MSI system to navigate remotely operated vehicles (ROVs) past unexpected obstacles in pipes. It is also useful in identifying any visual anomalies inside pipes.

Pipe penetrating radar uses high-frequency electromagnetic (EM) waves similar to how sonar uses sound waves. The reflected energy of the EM waves is recorded for analysis. PPR can be used to detect pipe wall fractures, changes in material, reinforcing location and placement, and pipe wall thickness. PPR may also detect the presence of voids developing outside the pipe. PPR can be deployed while the pipe is in service [39].

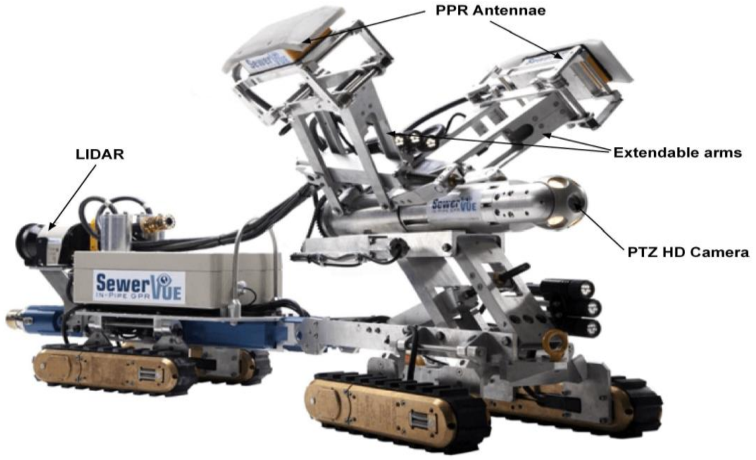

Figure 9: MultiSensor inspection system equipped with pan, tilt, zoom CCTV, LIDAR, and PPR. Adopted from SewerVUETechnology [39].

Name	Multisensor Inspection System
Purpose/Scope	Mainly used for wastewater pipes
Types of pipe it has been used for	Mainly used for wastewater pipes
Access to pipeline	Via manned entry or with remotely operated vehicles (ROVs).
Status	Commercially available [39]
Source of information	https://sewervue.com/multi-sensor-pipe-inspection-system.html
Advantages	• Material: All non-ferrous pipes (e.g. reinforced concrete, vitrified clay, asbestos cement, PVC, High density polyethylene (HDPE)) • Works under traffic noise/fluid turbulence: Yes • Single pipe/pipe network: Pipe network • Features/faults/pipe wall deterioration: can detect pipe wall fractures, wall thickness, rebar cover, delamination, voids etc. • Works on live network/drainage required: Works in live network • Range of pipelines on which this technique has been used: $200\ mm - 450\ mm$ • Long inspection distances: $2845\ \mathrm{m}$ • Frequency of reassessment: Periodic reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	Not available
Breadth of use	It has been used in Canada, Hong Kong and France. **This is available in NZ (Dunedin) and Australia.**

3.1.5.4 SurgeView

SurgeView is a non-invasive technique to monitor water networks for the presence of damping pressure surges [40]. It integrates multi-frequency pressure monitoring sensors (up to $256\ Hz$) to detect sources of damping pressure transients throughout a pipe network. These sensors can be easily deployed at optimal location across the network or in the vicinity of suspected sources of damping transients (i.e. for short-term monitoring or permanent monitoring). These sensors can be installed via existing hydrants, pipe taps or valves. Pressure data from sensors is transmitted wirelessly to the SurgeView^{TM} software [40].

Through SurgeView analysis, a water utility can get key insight into which hydraulic elements are causing damping transients, where are the sources, and whether those transients are stressing any parts of network-especially old pipe sections.

Name	SurgeView
Purpose/Scope	To monitor water networks for the presence of damping pressure surges
Types of pipe it has been used for	Water, wastewater or stormwater
Access to pipeline	Via hydrants, pipe taps or valves
Status	Commercially available [40]
Source of information	https://www.visenti.com/surgeview
Advantages	• Material: Any • Works under traffic noise/fluid turbulence: Yes • Single pipe/pipe network: Pipe network • Features/faults/pipe wall deterioration: For leaks and condition assessment • Works on live network/drainage required: Works in live network • Range of pipelines on which this technique has been used: Any size • Frequency of reassessment: Periodic/continuous reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	Not available
Breadth of use	It has been used in **Australia (SA Water and Yarra Valley water (Mitcham, Victoria)), NZ (Watercare, Christchurch City Council),** U.K. (Thames Water), Singapore (TUAS Power, Public Utility Board (PUB)) and UAE (Sharjah Electricity and Water Authority))

3.1.5.5 LeakView

The LeakView sensing technique is comprised of pipe leakage indicators such as high-rate pressure sensors, hydrophones, and flow metres for measuring multiple leaks [41]. These leakage indicators are generally installed at optimal locations coupled with data analytics for anomaly detection. These indicators can be installed on existing tapping points such as fire hydrants for distribution networks and trunk mains to detect and track losses. The sensing devices transmit continuous information about potential leaks in the pipe network to a data management and analytics engine. The LeakView system identifies the pressure transients, acoustic noise and flow enomalies related to breaks and localises them to the faulty pipe with high likelihood [41].

Name	LeakView
Purpose/Scope	To detect background existing leaks, leaks growing over time and newly occurring bursts
Types of pipe it has been used for	Water distribution and transmission mains
Access to pipeline	Via hydrants or pipe taps
Status	Commercially available [41]
Source of information	https://www.visenti.com/leakview
Advantages	• Material: Asbestos Cement, all metal pipes (such as cast iron, ductile iron, steel), and all plastic pipes (such as PE, HDPE, and PVC) • Works under traffic noise/fluid turbulence: Yes • Single pipe/pipe network: Pipe network

	• Features/faults/pipe wall deterioration: For leaks and burst detection • Works on a live network/drainage required: Works in live network • Range of pipelines on which this technique has been used: $\geq 100\ mm$ • Frequency of reassessment: continuous reassessment • Require skills/operator: Yes
Limitations	Data interpretation needs experience and skill.
Performance	Not available
Breadth of use	It has been used in **Australia (SA Water and Yarra Valley water (Mitcham, Victoria)), NZ (Watercare, Christchurch City Council),** U.K. (Thames Water), Singapore (TUAS Power, Public Utility Board (PUB)) and UAE (Sharjah Electricity and Water Authority))

3.2 Hydraulic Techniques (commercially available)

3.2.1 Unsteady State Hydraulic Methods

Transient events occur whenever flow or pressure conditions change in pressurised pipes. These events are interesting due to the fact that they both convey and send signals. Thus, by listening to the signal waves, it becomes easy to learn about system states and how they are coupled to physical attributes like the presence of a leak, a blockage or the status of pipe repair [14].

3.2.1.1 Pipe SONAR System

A piezoelectric actuator (a component of a machine that is responsible for moving and controlling a mechanism or system, for example by opening a valve) consisting of a vibrating ceramic element, referred to as Pipe SONAR, is a new approach for transient signal generation and can create customised, small amplitude ($< 400\ mm$) pressure signals that vary in frequency and magnitude. The measured responses to the generated signals are analysed with signal processing methods proposed in Lee [13]. Pipe SONAR is suitable for use on live water distribution networks and has been used commercially for valve and pipe wall condition assessment.

The piezoelectric actuator is driven by a linear power amplifier and an impedance matching unit. The generator and the data recording are controlled by customised software. One pressure sensor is located at the generator and another is attached to a hydrant. The Pipe SONAR system is attached to existing hydrants through a flanged connections. Pipe SONAR has been tested on two types of fire hydrants: below ground hydrants, typical in the United Kingdom, Australia and New Zealand; and above ground hydrants typical in America, China and mainland Europe [42].

Name	Pipe SONAR
Status	Commercially available
Purpose/Scope	For condition assessment and leak detection
Types of pipe it has been used for	Water (Main/transmission)

Source of information	Lee, et al. [43], Tuck [42], _ENREF_39
Advantages	• Material: asbestos cement (AC), cast iron (CI), ductile cast iron (DCI), PVC, reinforced concrete (RCP), and steel • Works under traffic noise/fluid turbulence: Yes • Can work on pipe network • Has been used for condition assessment of pipes and valves • Works on live network • Has been used for water pipes with diameter $100 - 600$ mm • Frequency of reassessment: continuous monitoring/condition based maintenance
Limitations	No information available
Performance	No information available
Breadth of use	**It has been used for condition assessment of pipes and valves in New Zealand** and China.

3.3 Non-hydraulic Leak Detection Techniques (Experimental Techniques)

3.3.1 Sensor Techniques

3.3.1.1 Pipe Condition Assessment Device

Pipe condition assessment device has been designed to assess the condition of individual pipes in a distribution system, including size and types of leaks present on the pipe, the efficacy of isolating valves and anomalies such as illegal connections and unrecorded network elements [44].

The pipe condition assessment device consists of various hydraulic and control components that are used to conduct a series of tests on a water distribution system pipe. The main device consists of a water tank, valves, pressure sensor and GPS unit linked to a central processing and communication unit. These components are installed on a hand-drawn trolley allowing it to be easily moved from one location to the next [44].

The second element of the device is an Android app that runs on a smartphone or tablet. The app guides the operators to the next pipe to be tested. It then assists the operators by identifying the hydrant to connect to, valves to close and house connections to isolate, through a GIS and GPS functionality [44].

The final element is a cloud-based management system that schedules the next pipe to be tested, links the app to the GIS data, manages the tests conducted and collects and analyses the test data [44].

The device is connected to an isolated pipe in a distribution system via a fire hydrant, scour valve or dedicated connection point, where it works through a sequence of actions to identify leaking valves, illegal connections, and the size and type of leaks present in a pipeline [44]. The information is gathered automatically to a central point via a GSM connection, where it is combined with GIS data of the system in order to facilitate water loss control and improved operation and maintenance practices.

To test and characterise leaks in a pipe, a pump is used to pressurise the isolated pipe section. If the pipe section has one or more leaks, water will move from the water source and through the device before leaving the pipe through leaks. Leaking valves are identified by checking whether the flow reduces to zero when a vent valve is opened. Pressurising the pipe at different levels allows leakage to be identified and characterised. The device has a variable speed pump and is able to measure both pressure and flow rate at different pump settings [44].

The test data is automatically sent to a cloud-based data management system for analysis. In this system results may be combined with GIS data of the system in order to facilitate water loss control and improved operation and maintenance practices [44].

The device can identify very small leaks and doesn't required highly skilled labour. Periodic reassessment allows the condition of pipes and valves to be monitored over time. The device has been tested in the laboratory and initial field trials in Cape Town, South Africa. However, it has not been applied to a significant area of a metropolitan scale .

3.3.1.2 Guided Wave Sensors

Guided wave ultrasonic testing (GWUT) has been applied for rapid screening of long lengths of pipework for corrosion and other defects [35]. The GWUT employs a mechanical stress wave that propagates along with an elongated structure while guided by the object's boundaries. The GWUT is operated at a low frequency (between$10 - 100kHz$). The method is attractive because it gives 100% coverage of the volume of the pipe within the diagnostic range of the test and tens of metres can be covered from a single transducer location [45]. The conventional application of the method is to use a removable transducer ring and to gain temporary access to the pipe at test locations spaced out along the pipeline [45]. To reduce the re-excavation costs, transducer rings can be installed permanently for continuous monitoring so that only one time access is needed [35]. This is known as a guided wave permanently installed monitoring system (gPIMS) [45]. The transducer is produced as a low profile flexible array, which can be bonded and clamped in place on the pipe surface. Then the transducer is sealed in a polyurethane jacket to provide complete protection [45]. gPIMS enables tracking and trending signal changes and allows for baseline subtraction [46]. The stability and sensitivity studies of gPIMS demonstrate the capabilities of the system to detect the circumferential distribution of wall loss, high probability of detection over a wide frequency range, and low probability of false indication [45].

The use of sensor technologies to the buried pipes has not been fully verified. Currently, acquisition of high-cost data is justified only for major transmission water mains, where the consequences of failure are significant [35]. Pipes with a low cost of failure do not justify expensive data acquisition campaigns. Another issue that requires attention is the lack of a full understanding of sensor reliability. Low cost and reliability are the most important factors in development of sensors for attachment to buried pipes [35].

Wireless Sensor Network

A wireless sensor network (WSN) consists of a large number of sensor nodes, which are deployed to collect and transmit data via wireless connections. Each sensor node is made up of a processing unit (microcontroller, memory, operating system, and so on), and an acquisition unit (sensor(s)), analogue-to-digital converter (ADC), transceiver(s) and a battery [47].

3.3.1.3 SmartPipes

SmartPipes is a sensor system that uses a wireless sensor network (WSN) for underground pipeline monitoring using force sensitive resistors. It is based on relative pressure sensor measurements combined with temperature difference measurements between the pipe and surrounding medium, to detect a leak in a pipe buried in the field. These sensors are so far used for leak detection and leak localisation in plastic pipes. This pressure sensing method has been investigated for its performance and capabilities by both laboratory and field trials [48].

This method allows easy installation of the sensor nodes on pipes without jeopardising the pipes' structural integrity [48].

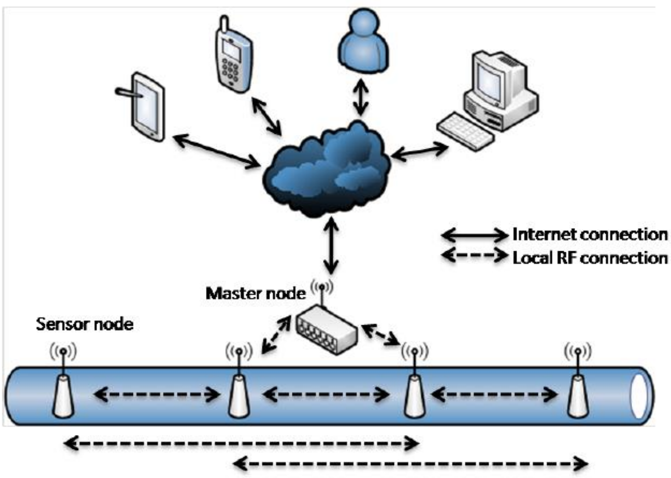

Figure 10: General Schematic of SmartPipes sensor network for a pipeline monitoring system. Adopted from Sadeghioon, et al. [48].

3.3.1.4 TriopusNet

TriopusNet is a mobile wireless system for autonomous sensor deployment in pipeline monitoring. It works by automatically releasing sensor nodes from a centralised repository located at the source of the water pipeline (Tsung-Te Lai, et al. [49]). During automated deployment, TriopusNet runs a sensor deployment algorithm to determine node placement. Each mobile sensor node in TriopusNet is equipped with one motor that drives three arms (as shown in Figure 11). These arms can be extended for the purpose of latching a traveling sensor node onto the pipe's inner surface, thereby fixing the node placement [49]. By continuously releasing nodes into pipes, the TriopusNet system builds a wireless network of interconnected sensor nodes.

When a node runs at a low level or experiences a fault, the TriopusNet system releases a fresh node from the repository and runs a node replacement algorithm to replace the failed node with the fresh one [49]. TriopusNet is able to use fewer sensor nodes to cover a sensing area in the pipes while maintaining network connectivity among nodes with high data collection rate. TriopusNet scales down human effort in deploying and maintaining WSN infrastructure inside pipes [49]. However, the benefits and feasibility of TriopusNet has been tested using an experimental study.

Figure 11: An overview of TriopusNet. The sensor nodes are released from the water inlet points. Adopted from Tsung-Te Lai, et al. [49].

3.4 Hydraulic Techniques (Experimental Techniques)

3.4.1 Steady State Methods

3.4.1.1 Mass Balance Method

Mass balance is the most commonly used steady state leak detection method due to its simplicity. The basic principle behind this method is that the total volume entering a pipeline must be equal to the total volume exiting [13]. If there is a difference, then a leak exists. While this method is useful for leak detection, it cannot find leak locations. For the leak to be located, the network must be broken down into subsections, each supplied by single supply main. A mass audit is performed for each subsection and a stepwise elimination method is used to gradually remove the subsections that are free from the leaks. This method can be time consuming as a volumetric system balance must be performed over a significant period of time to minimise errors. A full water audit may take a number of months to successfully isolate a problem to a single pipe section. Also, the accuracy of this method hinges on the accuracy of the measuring instrument and size of the leak.

3.4.1.2 Line Pressure Measurement Method

Line pressure measurements are often used in conjunction with the mass balance method. A leak reduces flow downstream and changes the slope of the hydraulic grade line. Predicted hydraulic grade lines from flow measurements can be compared to pressure measurements taken at particular points along with the system. Discrepancies between the two are indicative of leaks [13].

These steady state techniques are successful in controlled situations, however, such techniques have proven difficulties in operating pipelines. The primary problem with these techniques is that each measurement station under steady state flow results only in a single data point. A higher number of measurement stations and several experiments under different conditions are required to produce sufficient data for analysis [13].

3.4.2 Unsteady State Hydraulic Methods

3.4.2.1 Transient Reflection Method (TRM)

The transient reflection method (TRM), which is also referred to as the time-domain reflectometry (TDM) is a method whereby the system response is analysed in the time domain and a fault can be detected by the signal reflected from it. TRM relies on the differentiation of a referred signal by identifying the discrepancies between measured results with the fault-free benchmark results. The benchmark results can be obtained from a fault-free laboratory system, or from an accurate numerical model of the pipe system [14].

Brunone [50] introduced the theory to use the generated transient to detect leaks by measuring the arrival time of a reflected wave and verified it by an experiment in a single polyethylene pipe, while the background noise disturbed the identification of signals. The experimental validation was improved by Brunone and Ferrante [51] to identify the leak location more accurately. Beck, et al. [52] used the cross-correlation method to reduce the problem of disturbance and detected more pipeline features in a T-junction network. Meniconi, et al. [53] applied the TRM to detect the location of an illegal side branch in a complex laboratory pipe system. The experiment performed well, but uncertainty about factors like friction and unaccounted for reflections in real systems may complicate practical application. Recent studies have improved the application of TRM by utilising methods and algorithms such as cepstrum analysis [54], wavelet analysis [55, 56], cumulative sum method [57], and curve fitting based on artificial neural networks [58].

TRM methods are so far used only in single pipe case studies in laboratory conditions [14].

3.4.2.2 Transient Damping Method (TDM)

In TDM it is analytically derived that friction related transient damping in a pipeline without a leak is exponential and the corresponding damping in a pipeline contacting a leak is approximately exponential [59]. Faults usually modifies the damping pattern, so they can be detected by comparing the induced damping pattern with the fault-free benchmark in the same pipeline system. The rate of the leak-induced damping depends on leak characteristics, the pressure in the pipe, the location of the transient generation point and the shape of the generated transients [12]. The transient damping approach introduced by Wang, et al. [59] performed a Fourier series analysis to solve the linearised differential equations.

Tests on a laboratory pipeline showed successful leak detection but in a real situation, friction is not the only cause of transient damping. Transient damping can be caused by other physical elements like joints, connections, fire hydrants, and pipe wall deterioration. The modelling of these elements can be complicated and in some cases even impossible. Therefore it may be difficult to estimate the leak-free damping for a real pipeline.

3.4.2.3 System Response Method (SRM)

The main principle of the system response method (SRM) is to utilise all the information (i.e. reflection and damping effects) contained in the transient signal of the system response to identify and locate the faults by comparing the results from a pipeline with and without faults [14]. The pipe system is considered as a transformation that can produce an output of the measured pressure response by using each given input of the transient injected to the system. A complicated input is divided into a series of weighted unit impulses, and the overall system response is obtained by a process known as convolution, which adds the contributions from the entire input signal. The function relating the input and output signals indicates all information about the behaviour and features of the pipe systems [14].

The impulse response function (IRF) converts the output signal in the trace into sharp impulses with well-defined spikes. The IRF is found by a process known as deconvolution, however this is complicated for finding the IRF for the original system output. This can be done alternatively by first finding the Frequency response function (FRF) and removing the high frequency components which correspond to the system noise [42]. IRF has been used previously for real-time single pipeline leak detection by Liou [60]. Kim [61] integrated genetic algorithm into the impulse response method (IRM) in which location and size of a leak were calibrated. Lee, et al. [57] validated the IRM using an experimental study and demonstrated the impact of single bandwidth and background noise on extracted IRF. Experimental study for a single pipeline using IRF to detect distributed deterioration by determining the variation of pipe wall thickness was done by Gong, et al. [62].

The lack of information about tests in real pipeline systems where noisy data would be used makes it a less viable method when compared with the Transient Reflection Method (TRM) and Inverse Transient Method (ITM). The IRF has the advantage that it is independent of the input signal shape and is specific for each pipe system [57].

The frequency response function (FRF) method for leak detection examines the transient response of a system in the frequency domain. Lee, et al. [63] introduced two transient leak detection techniques for locating single as well as multiple leaks by explaining the nature of resonance peaks in a frequency response diagram. Duan, et al. [4] observed the blockage-induced changes to the resonant frequencies and developed another method for blockage detection. The resonant frequency shifts caused by blockages in a pipe system is studied by conducting a transient wave perturbation analysis. The accuracy of the method has been validated using numerical application and experimental tests [4].

Unlike the IRM, the performance of FRM is closely related to the shape of the input transient. FRM analyses transient response in the frequency domain, and it is equivalent to the IRM in the time domain describing the system response from a transient excitation [14].

3.4.2.4 Inverse Transient Method (ITM)

In the inverse transient method (ITM), first, the transient state is initiated by opening or closing a controlled valve over a short time period. Afterwards, transient pressure fluctuations are measured at multiple selected points in the system [14]. The measurement points are usually located close to the transient generation point. The transient condition of the pipe system is then numerically modelled as a function of pipeline features, fault parametres, and friction factors. The location and size of the leaks are determined by the minimisation of the deviation between the measured and calculated pressure data.

The ITM is a well-researched topic but since its beginning, the main effort has been focused on the development of the mathematical part of the technique and not an experimental validation or field testing [64]. The tests are made on a single pipeline rather than on a network. Application difficulties lie in the fact that ITM needs an accurate modelling of the transients and boundary conditions of the pipe systems.

Factors influencing effectiveness of unsteady state hydraulic methods

Condition monitoring using fluid transients requires the generation of highly controlled pressure signals in the field, often against significant system back pressure and a confusing array of background traffic and fluid turbulence noise [42]. Since most water pipelines run alongside traffic routes, the generation of the signal should be carried out quickly, non-intrusively and with a minimal loss of water. This combination of requirements poses significant challenges for researchers in the field and transient tests were often carried out in the middle of the night where the background noise and traffic volume are low [42].

4 Evaluation of Techniques

Table 1: Detailed summary of Condition Assessment Technologies for Water Transmission, Distribution and Wastewater Conveyance Pipelines

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
Visual inspection	Assesses the condition of the internal or external surface of a pipe by visual inspection									
a. CCTV Pipe Inspection	Visual inspection via internal condition assessment of a pipe	• Works under traffic noise • Air and gas pockets and leak detection • Works on live network • Highly sensitive leak detection to the smallest leak • No pre-cleaning of a pipe is needed	• Requires skills and operator • Intrusive technique • Operates in up to 100 bar pressure environments	Any	150 to 3000 mm	Via an existing air valve or similar entry		All 3 types of pipes	Available in NZ.	http://www.detectionservices.com.au/services/pipeline-condition-assessment/pipe-inspector/
Acoustic inspection	Uses sound waves to determine the location and extent of flaws in pipes									
a. Free-Swimming Leak Detection Device	Detects leaks and air pockets in medium and large diameter pipes	• Can survey long pipelines with a single deployment • Can detect very small noise disturbances • Can be used while in service	• May not work in very high water pressure (> $400\ PSI$) • For very long pipe length, may require a surface sensor • Estimation of leak magnitude is qualitative • Intrusive technology	Any	≥200 mm	Insertion and extraction points, valve, hot tap connection	High	Water and Wastewater		https://puretechltd.com/technology/smartball-leak-detection/

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
b. Tethered Leak Detection Tool	Inspects in-service water mains for leaks, air pockets, visible defects, and wall thickness of metallic pipe using tethered equipment	• Sensitive to small leaks • Surface tracking can map the pipeline under inspection • Can be used for any pipe size > $150\ mm$ • Can be used while in service	• Intrusive technology • Requires access point (insertion point) • Ground cover up to $10\ m$	Any	$> 150\ mm$	One insertion point	High	Water and Wastewater		https://puretechltd.com/technology/sahara-leak-gas-pocket-detection/
c. Leak Noise Correlators (Technique – 1)	A system for locating leaks in all types of pipes	• Works under traffic noise • Works in live networks • Identifies all minor and major leaks • Non-intrusive technique • Uses a low-frequency vibration sensor to locate leaks in plastic pipes	• Information about the leak size is not available from the test • Sensor spacing is influenced by both the pipe diameter and material • May be susceptible to interference from low frequency vibration	Any		Via fire hydrant		Water mains	Commercially used in Australia, the U.K. and other countries. **Not available in NZ.**	Hunaidi, et al. [25] https://www.echologics.com/products/leakfinderst/
d. Leak Noise Correlators (Technique – 2)	Identifies leaks for a variety of pipe materials and large diameter mains	• Works under traffic noise • Works on live network • Can find any types of leaks		Any	$100\ to\ 300\ mm$	Via fire hydrant		Water mains	Commercially used in the U.S.A and Canada. **Not available in NZ.**	https://www.echologics.com/services/small-diameter-leak-monitoring/echoshore-dx/
e. Leak Noise Correlators (Technique – 3)	For leak detection in all transmission main pipelines	• Works under traffic noise • Works on live network • Identifies all minor and major leaks •		Any	$> 400\ mm$	Via existing chamber, purpose-built access, above ground utility box, and direct to pipe		Transmission main	Commercially used in the U.K., the U.A.E., the U.S.A., the Netherlands, Singapore, and Canada. **Not available in NZ.**	https://www.echologics.com/services/large-diameter-leak-detection/echoshore-tx/

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
f. Pipeline Condition Assessment Technique	For condition assessment and finding leaks of transmission and distribution mains	• Works under traffic noise • Works on live network • Identifies all minor and major leaks		Metallic, AC, Cast Iron, Ductile Iron, Steel and mortar lined, and pre-stressed concrete	$400\ to\ 2200\ mm$			Water transmission and distribution mains	Commercially used in the U.S.A. **Not available in NZ.**	https://www.echologics.com/services/condition-assessment/epulse/
Electromagnetic Techniques	Inspects ferromagnetic pipes using electromagnetic technology									
a. Free-Swimming Tool	For condition assessment of PCCP and metallic pipes (Ductile Iron and Steel)	• Can detect broken wire wraps, sedimentation, corrosion, anomaly and remaining pipe life • Works on live network	• Data interpretation needs experience and skill.	PCCP and metallic pipes (ductile iron and steel)	$400\ to\ 3000\ mm$	Via chamber, open channel or small hot tap		Water and Wastewater	Commercially used in the U.S.A., the U.K., Canada and the Netherlands. **Not available in NZ.**	https://puretechltd.com/technology/pipediver-condition-assessment/ https://www.wrc-infrastructure.co.uk/technologies/pipediver%C2%AE/
b. Remote Field Testing	Inspects ferromagnetic pipes and ferromagnetic components of composite pipes	• Can detect broken wire wraps, sedimentation, corrosion, anomaly and remaining pipe life • Works on live network	• Data interpretation needs experience and skill.	PCP, cast iron	50 to 3000 mm	Via chamber, open channel or small hot tap		Water and Wastewater	Commercially used in the U.S.A., the U.K., Canada and the Netherlands. Not available in NZ.	https://www.russelltech.com/News/PID/719/ev/1/TagID/7/TagName/See-Snake
c. Pipe Penetrating Radar (PPR)	PPR can be used to detect pipe wall fractures, changes in material, reinforcing location and placement, and pipe wall thickness	• Works on live network	• Data interpretation needs experience and skill.	All non-ferrous pipes (e.g. reinforced concrete, vitrified clay, asbestos cement, PVC, High density polyethylene (HDPE))	$200\ to\ 450\ mm$	Via manned entry or with remotely opera-ted vehicles (ROVs).		Water and Waste Water		https://sewervue.com/pipelines2017-presentation-ppr.html

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
Fibre Optics Sensing Techniques	Involves the installation of a fibre optic cable to measure the temperature over the entire pipeline length									
a) Integrated Smart Monitoring Technique	Mainly used for water transmission and distribution mains for leak detection	• Works on live network • Works on single pipes and pipe networks		Any	All diameter range	via specially installed messenger pipe called Atlantis Hydrotec		Water transmission and distribution main	Commercially used in Spain. **Not available in NZ.**	https://www.craley.com/aiguees-vic-choose-ism-for-leak-det
Sensor Techniques	Time-based techniques for the inspection, monitoring and condition assessment of buried pipes									
a. inSCAN	For leak detection and pipe condition assessment	• Works on live network • Can work on pipe networks • Long inspection distance up to 14 km of a pipeline • Can detect all types of leaks, air pockets, blockages, debris, and condition assessment	• Data interpretation needs experience and skill.	Any	$\geq 300\ mm$	Via 50 mm or larger tapping or valve		Water transmission (mainly trunk mains) and waste water	**Commercially available in Australia and NZ**	http://www.detectionservices.com.au/services/pipeline-condition-assessment/inscan/

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
b. p-CAT	For pipe condition assessment	• Can work on pipe networks • Long inspection distance up to 14 km of a pipeline • Can determine remaining thickness of pipe wall to 0.2 mm accuracy over long section of a pipeline • Can detect deterioration, pipe material changes, cement material changes, cement matric loss from AC pipes, blockages, air and gas pockets	• Data interpretation needs experience and skill.	Concrete and AC pipes	$\geq 400\ mm$	Via air valves		Water transmission (mainly trunk mains) and waste water	**Commercially available in Australia and NZ**	http://www.detectionservices.com.au/services/pipeline-condition-assessment/p-cat/
c. Multisensor Inspection (MSI) System	Mainly used for detecting defects and cavities for non-ferrous pipes of all shapes and sizes	• Can work on live pipe networks • Can detect pipe wall fractures, wall thickness, rebar cover, delami-nation, voids • Long inspection distance up to 3 km of a pipeline	• Data interpretation needs experience and skill.	reinforced concrete, vitrified clay, AC, PVC, High density polyethylene	$200\ to\ 450\ mm$	Via manned entry or with remotely operated vehicles (ROVs)		Waste water	Commercially available in Canada, Hong Kong and France. **Not available in NZ.**	https://sewervue.com/multi-sensor-pipe-inspection-system.html
d. SurgeView	To monitor water networks for the presence of damping pressure surges	• Can work on live pipe networks • For pipe leak detection and condition assessment	• Data interpretation needs experience and skill.	Any	Any	Via hydrants, pipe taps or valves		Water, waste water, storm water	Commercially available in **Australia, NZ,** the U.K., Singapore, and UAE	https://www.visenti.com/surgeview

Condition Assessment Technology	Description	Advantages	Disadvantages	Pipe Material Suitable	Pipe Diameter Suitable	Access	Accuracy *	Water/ Waste-Water/ Storm-Water	Breadth of use	Source of information
e. LeakView	To detect background existing leaks, leak growing over time and newly occurring burst	• Can work on live pipe networks • For pipe leak detection	• Data interpretation needs experience and skill.	AC pipes, All metal pipes, and all plastic pipes	$\geq 100\ mm$	Via hydrants, pipe taps		Water distribution, and transmission mains	Commercially available in **Australia, NZ,** the U.K., Singapore, and UAE	https://www.visenti.com/leakview
Unsteady state Hydraulic techniques	For the purpose of pipe fault detection by using the sound generated through the pipeline operation or through continuous discharge of water to specifically generate a pressure wave									
a. Pipe SONAR system	piezoelectric actuator for transient signal generation	• Can work under traffic noise and fluid turbulence • Used for condition assessment of pipes and valves • Works on live network		AC, Cast iron, ductile iron, PVC, reinforced concrete, steel	100 to 600 mm	Via fire hydrant		Water distribution and transmission mains	**Commercially available in NZ** and China	

* H= High degree of Accuracy (approximately >80%), M= Moderate degree of accuracy (approximately 50%), L= Low degree of accuracy (approximately 10%)

5 Conclusions

As water pressure pipe networks age, they are exposed to continuous stress from operational and environmental conditions. As a consequence, these systems may deteriorate structurally and hydraulically, adversely impacting water quality, leakage, and reliability. Effective management of these assets requires condition assessment, which includes the collection of information on their condition, analysis of that information, and transformation of this information into knowledge, leading to effective decisions regarding renewal.

This report summarises available condition assessment technologies for New Zealand's pressurized water network, including transmission and water mains. The detailed description of the performance of each technology is provided in Section 3 and a summary of each technology in Table 1. There are currently a number of technologies that are commercially available internationally for leak detection and structural integrity monitoring of water pressure pipe networks. However, the results of a survey conducted by the BIP of NZ councils, asking them to identify the number of techniques currently used by them for assessing the condition of pressure pipe, revealed that only a few techniques out of those listed in this report have been used. Techniques for condition assessment of pressure pipes currently used by NZ councils, according to the respondents of the survey, are as follows:

- Pipe cut-off samples for testing pipe condition (CT scan)
- Desktop assessment based on AC pipe manual guidelines [65]
- Opportunistic visual inspection information obtained when a pipe fails/bursts
- Monitoring water main failure through asset management systems, seeking to identify root causes of failure and undertaking statistical sampling
- Hydrant flow testing of cast iron mains to monitor tuberculation, and through sampling to determine asset condition of the pipe
- Using sensor techniques for leak detection provided by Visenti [41]

However, no specific recommendations are made or implied by this report. Utility owners are encouraged to undertake their own due diligence on each approach, to determine their specific needs and to consider the accuracy, cost effectiveness, track record and other specific requirements of the various technologies, when planning their condition assessment program.

6 Bibliography

[1] Water New Zealand, "Water NZ 2017-2018 National Performance Review," Water New Zealand, Wellington 2018, Available: https://www.waternz.org.nz/NationalPerformanceReview.

[2] P. McFarlane, "Wastewater Renewals Framework – Gravity Pipelines," Auckland, New Zealand2018.

[3] R. A. Silva, C. M. Buiatti, S. L. Cruz, and J. A. Pereira, "Pressure wave behaviour and leak detection in pipelines," *Computers & chemical engineering,* vol. 20, pp. S491-S496, 1996.

[4] H. F. Duan, P. J. Lee, M. S. Ghidaoui, and J. Tuck, "Transient wave-blockage interaction and extended blockage detection in elastic water pipelines," *Journal of fluids and structures,* vol. 46, pp. 2-16, 2014.

[5] P. Zane Satterfield, "Fundamentals of Hydraulics Flow," *Tech Brief,* vol. 10, no. 1, pp. 1-4, 2010.

[6] T. M. Walski, D. V. Chase, D. A. Savic, W. Grayman, S. Beckwith, and E. Koelle, "Advanced water distribution modeling and management," 2003.

[7] American Water Works Association, *Water transmission and distribution*. American Water Works Association, 2003.

[8] N. S. Grigg, *Water, wastewater, and stormwater infrastructure management*. CRC Press, 2012.

[9] BRANZ. *Water use, sustainability, and efficiency by choosing quality systems and materials, and providing environmentally friendly solutions*. Available: http://www.level.org.nz/water/water-supply/system-layout-and-pipework/pipe-materials/

[10] Ministry for the Environment, "Measuring and Reporting Water Takes: An Introduction to the Resource Management (Measurement and Reporting of Water Takes) Regulations 2010," INFO 617, October 2010, Available: https://www.mfe.govt.nz/publications/rma-fresh-water/measuring-and-reporting-water-takes-introduction-resource-management.

[11] Ministry of Health, *Pumps, Pipes and Storage: Resources for Drinking-water Assistance Programme* Wellington: Ministry of Health, 2010.

[12] R. Puust, Z. Kapelan, D. Savic, and T. Koppel, "A review of methods for leakage management in pipe networks," *Urban Water Journal,* vol. 7, no. 1, pp. 25-45, 2010.

[13] P. J. Lee, "Using system response functions of liquid pipelines for leak and blockage detection," 2005.

[14] C. Verde and L. Torres, *Modeling and Monitoring of Pipelines and Networks*. Springer, 2017.

[15] Y. Kleiner and B. Rajani, "Comprehensive review of structural deterioration of water mains: statistical models," *Urban water,* vol. 3, no. 3, pp. 131-150, 2001.

[16] J. Mora-Rodriguez, X. Delgado-Galvan, H. M. Ramos, and P. A. Lopez-Jimenez, "An overview of leaks and intrusion for different pipe materials and failures," *Urban Water Journal,* vol. 11, no. 1, pp. 1-10, 2014.

[17] A. B de Almeida and H. Ramos, "Water supply operation: Diagnosis and reliability analysis in a Lisbon pumping system," *Journal of Water Supply Research and Technology-aqua,* vol. 59, 02/01 2010.

[18] N. A. Barton, T. S. Farewell, S. H. Hallett, and T. F. Acland, "Improving pipe failure predictions: Factors effecting pipe failure in drinking water networks," *Water research,* p. 114926, 2019.

[19] D. B. Garcia and I. D. Moore, "Leakage Performance of Joints in Gravity Flow Pipes Subjected to Shear Force, Angular Misalignment, and Diameter Deformation," *Journal of Testing and Evaluation,* vol. 47, no. 4, pp. 2808-2826, 2018.

[20] R. Fletcher and M. Chandrasekaran, "SmartBall™: a new approach in pipeline leak detection," in *2008 7th International Pipeline Conference*, 2008, pp. 117-133: American Society of Mechanical Engineers.

[21] PureTechnologies. (2009). *SmartBall for Water Leak Detection* Available: https://puretechltd.com/water-and-wastewater/solutions/pipeline-condition-assessment/

[22] Z. Liu and Y. Kleiner, "State of the art review of inspection technologies for condition assessment of water pipes," *Measurement,* vol. 46, no. 1, pp. 1-15, 2013.

[23] D. Ellison, *Manual of Water Supply Practices—M77 Condition Assessment of Water Mains*, First ed. American Water Works Association, 2019.

[24] Z. Liu, Y. Kleiner, B. Rajani, L. Wang, and W. Condit, "Condition assessment technologies for water transmission and distribution systems," *United States Environmental Protection Agency (EPA),* vol. 108, 2012.

[25] O. Hunaidi, A. Wang, M. Bracken, T. Gambino, and C. Fricke, "Acoustic methods for locating leaks in municipal water pipe networks," in *International conference on water demand management*, 2004, pp. 1-14: Dead Sea Jordan.

[26] S. Perrier, M. Moslemi, B. Robertson, V. Burtea, and I. Moore, "Characterization of Soil Attenuation for Acoustic Condition Assessment of Water-Filled Metal Pipes," *26th International Conference on Sound and Vibration, Montreal, QC, July 7-11.,* 2019

[27] O. Hunaidi, M. Bracken, and A. Wang, "Non-destructive testing of pipes," ed: Google Patents, 2008.

[28] ECOLOGICS. *Continuous Leak Detection Monitoring for Distribution Mains*. Available: https://www.echologics.com/services/small-diameter-leak-monitoring/echoshore-dx/

[29] O. Hunaidi, "Detecting leaks in water-distribution pipes," *Construction Technology Update,* vol. 40, pp. 1-6, 2000.

[30] PureTechnologies. (2011). *PipeDiver for Force Main Inspection*. Available: https://puretechltd.com/technology/pipediver-condition-assessment/

[31] W. Wang, J. Boon, and X. Kong, "Condition Assessment of Live PCCP Lines with Free-Swimming Electromagnetic Inspection System," in *ICPTT 2012: Better Pipeline Infrastructure for a Better Life*, 2013, pp. 1-7.

[32] B. Mergelas and X. Kong, *Electromagnetic inspection of prestressed concrete pressure pipe*. American Water Works Association, 2001.

[33] SewerVUETechnology. (2011). *Revolutionary Pipeline Condition Assessment*. Available: https://sewervue.com/pipe-penetrating-radar.html

[34] CraleyGroup. (2018). *iSM^{TM} Inpipe Leak Detection and Asset Security* Available: https://www.craley.com/ism-leak-detection

[35] Z. Liu and Y. Kleiner, "State-of-the-art review of technologies for pipe structural health monitoring," *IEEE Sensors Journal,* vol. 12, no. 6, pp. 1987-1992, 2012.

[36] DetectionServices. *inSCAN Pipe Condition Assessment and Leak Location System* Available: http://www.detectionservices.com.au/services/pipeline-condition-assessment/inscan/

[37] DetectionServices. (2016). *p-CAT pipeline condition assessment* Available: http://www.detectionservices.com.au/services/pipeline-condition-assessment/p-cat/

[38] C. Ekes, "New Developments in Multi-Sensor Condition Assessment Using LiDAR, Sonar, and CCTV," in *Pipelines 2017*, 2017, pp. 23-29.

[39] SewerVUETechnology. (2017). *New Developments in Multi-Sensor Condition Assessment using LIDAR, Sonar, PPR and CCTV*. Available: https://sewervue.com/pipelines2017-presentation-msi.html

[40] Visenti. *Surgeview-identifying and predicting assets that are in poor condition and likely to break*. Available: https://www.visenti.com/surgeview

[41] VisentiLeakView. *LeakView real-time pipe failure detection* Available: https://www.visenti.com/leakview

[42] J. Tuck, "Field application of transient analysis methods for pipeline condition assessment," 2016.

[43] P. Lee, J. Tuck, M. Davidson, and R. May, "Piezoelectric wave generation system for condition assessment of field water pipelines," *Journal of Hydraulic Research,* vol. 55, no. 5, pp. 721-730, 2017.

[44] L. Lopez and J. van Zyl, "Pressure-Based Pipe Condition Assessment for Intelligent Water Network Maintenance," in *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making*, 2019, pp. 491-497: ICE Publishing.

[45] M. Evans and K. Vine, "Permanently installed transducers for guided wave monitoring of pipelines," in *10th European conference on Non-destructive testing, Moscow, Russia*, 2010, pp. 1-6.

[46] A. Galvagni and P. Cawley, "Guided wave permanently installed pipeline monitoring system," in *AIP Conference Proceedings*, 2012, vol. 1430, no. 1, pp. 1591-1598: AIP.

[47] E. Popovici, M. Magno, and S. Marinkovic, "Power management techniques for wireless sensor networks: a review," in *5th IEEE International Workshop on Advances in Sensors and Interfaces IWASI*, 2013, pp. 194-198: IEEE.

[48] A. Sadeghioon, N. Metje, D. Chapman, and C. Anthony, "SmartPipes: smart wireless sensor networks for leak detection in water pipelines," *Journal of sensor and Actuator Networks,* vol. 3, no. 1, pp. 64-78, 2014.

[49] T. Tsung-Te Lai, W.-J. Chen, K.-H. Li, P. Huang, and H.-H. Chu, "TriopusNet: automating wireless sensor network deployment and replacement in pipeline monitoring," in *2012 ACM/IEEE 11th International Conference on Information Processing in Sensor Networks (IPSN)*, 2012, pp. 61-71: IEEE.

[50] B. Brunone, "Transient test-based technique for leak detection in outfall pipes," *Journal of water resources planning and management,* vol. 125, no. 5, pp. 302-306, 1999.

[51] B. Brunone and M. Ferrante, "Detecting leaks in pressurised pipes by means of transients," *Journal of hydraulic research,* vol. 39, no. 5, pp. 539-547, 2001.

[52] S. Beck, M. Curren, N. Sims, and R. Stanway, "Pipeline network features and leak detection by cross-correlation analysis of reflected waves," *Journal of hydraulic engineering,* vol. 131, no. 8, pp. 715-723, 2005.

[53] S. Meniconi, B. Brunone, M. Ferrante, and C. Massari, "Transient tests for locating and sizing illegal branches in pipe systems," *Journal of Hydroinformatics,* vol. 13, no. 3, pp. 334-345, 2011.

[54] M. Taghvaei, S. B. M. Beck, and W. J. Staszewski, "Leak detection in pipelines using cepstrum analysis," *Measurement Science and Technology,* vol. 17, no. 2, pp. 367-372, 2006/01/04 2006.

[55] M. Ferrante and B. Brunone, "Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis," *Advances in Water Resources,* vol. 26, no. 1, pp. 107-116, 2003.

[56] M. Ferrante, B. Brunone, and S. Meniconi, "Wavelets for the Analysis of Transient Pressure Signals for Leak Detection," *Journal of Hydraulic Engineering,* vol. 133, no. 11, pp. 1274-1282, 2007.

[57] P. J. Lee, M. F. Lambert, A. R. Simpson, J. P. Vítkovsky, and D. Misiunas, "Leak location in single pipelines using transient reflections," *Australasian Journal of Water Resources,* vol. 11, no. 1, pp. 53-65, 2007/01/01 2007.

[58] I. Stoianov, B. W. Karney, D. Covas, C. Masksimovic, and N. Graham, "Wavelet processing of transient signals for pipeline leak location and quantification," presented at the International Conference on Computing and Control for the Water Industry (CCWI 2001), Leicester, UK, , 2001.

[59] X.-J. Wang, M. F. Lambert, A. R. Simpson, J. A. Liggett, and J. P. Vitkovsky, "Leak detection in pipelines using the damping of fluid transients," *Journal of Hydraulic Engineering,* vol. 128, no. 7, pp. 697-711, 2002.

[60] C. P. Liou, "Pipeline leak detection by impulse response extraction," *Journal of Fluids Engineering,* vol. 120, no. 4, pp. 833-838, 1998.

[61] S. H. Kim, "Extensive Development of Leak Detection Algorithm by Impulse Response Method," *Journal of Hydraulic Engineering,* vol. 131, no. 3, pp. 201-208, 2005.

[62] J. Gong, A. R. Simpson, M. F. Lambert, A. C. Zecchin, Y.-i. Kim, and A. S. Tijsseling, "Detection of Distributed Deterioration in Single Pipes Using Transient Reflections," *Journal of Pipeline Systems Engineering and Practice,* vol. 4, no. 1, pp. 32-40, 2013.

[63] P. J. Lee, J. P. Vitkovsky, M. F. Lambert, A. R. Simpson, and J. A. Liggett, "Frequency domain analysis for detecting pipeline leaks," *Journal of Hydraulic Engineering,* vol. 131, no. 7, pp. 596-604, 2005.

[64] A. F. Colombo, P. Lee, and B. W. Karney, "A selective literature review of transient-based leak detection methods," *Journal of hydro-environment research,* vol. 2, no. 4, pp. 212-227, 2009.

[65] Water New Zealnd, *National Asbestos Cement Pressure Pipe Manual* Second ed. 2017.