PAPER 13

CAUSES OF LEAKS AND LEAKAGE MANAGEMENT IN WATER DISTRIBUTION SYSTEMS

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ABSTRACT

This paper presents the outcomes of simultaneous application of various leak detection technologies applied in Rand Water distribution System to manage water losses, in order to reduce water leakages in pipeline network. The study is aimed at investigating the causes of leaks in Rand Water distribution network and exploring effective and economical methods to reduce the avoidable Non- Revenue Water (NRW). As part of managing NRW, a programme of leak detection and repairs which formed part of reactive measures, was established using various leak detection technologies in discrete water pipelines. The leak detection technologies that were used include Sahara technology, SmartBall technology, piper technology as well as the satellite technology. In addition, different technologies which formed part of proactive measures were also used, such as Long Range Guided Ultrasonic Waves (Gul) Technology and Magnetic Tomography Method (MTM) Gradient were used to determining the wall thickness on the pipes in order to action the appropriate method of repairs to prevent pipe from leaking. Several leaks were detected and pinpointed on the ground, and the results demonstrated that with the use of these different leak detection technologies and repairing methods, Rand Water will be able to reach their target of reducing avoidable Non-Revenue Water. Rand Water's target is to reduce the NRW from 7% to 3% and this could save the organisation an estimate amount of over R846 million Rands of annual loss.

***Keywords**: Leaks, water distribution networks, leak detection technologies, Non-Revenue Water.*

1. INTRODUCTION AND BACKGROUND

A large amount of potable water is lost through leakage in water distribution in South Africa and in the world. Leakage from water distribution systems accounts for a significant portion, sometimes more than 70% of the total losses (WHO-World Health Organisation, 2001). In South Africa, for instance, the NRW is around 41% (Department of Water Affairs, 2017 Report).

There are many factors contributing to the physical mechanism failure in water distribution networks which are the causes of leaks namely: age of pipes, operational pressure in relation to design pressure, excessive pressure, and pressure surges, quality of pipe materials, corrosion, poor construction, ground conditions and ground movement, vibration and traffic loading, depth of pipe installation, defects in pipes, damage due to excavations, poor quality of joints, and changes in temperature due to climate change. Common to all above mentioned factors is the development of defects that create water leakage, especially within the pipes (Samir, N. et al, 2017).

Leakage in water distribution systems is sensitive to pressure. Thus, an understanding of pressure-leakage relationships is therefore fundamental to a system approach leakage control. In the past, leakage was seen as not being sensitive to pressure (Van Zyl, J.E. and Clayton, C. 2007). However, it has been shown in various studies to be very sensitive to pressure, than theoretically described by the orifice equation in 1.1 below (Van Zyl, J.E. and Clayton, C. 2007). Pressure and leakage relationship is illustrated in figure 1 below (Lambert A., 1997):

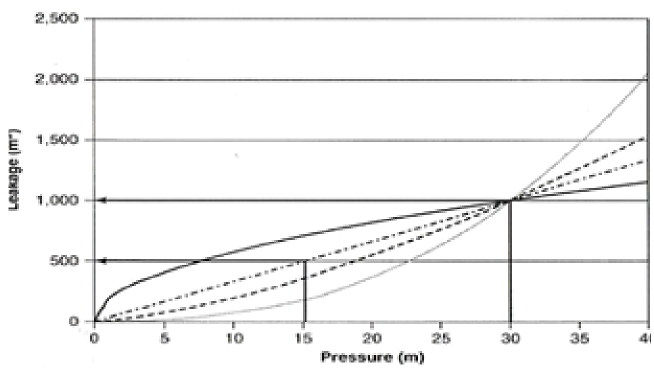

FIGURE 1: *The relationship between leakage and pressure (Lambert A., 1997)*

Van Zyl and Clayton found that different mechanisms may be responsible for this pressure-l eakage relationship, which are leakage hydraulics, pipe material behaviour, soil hydraulics and water demand management. It was therefore concluded that the pipe material behaviour plays a major role in the observed behaviour leakage area (Van Zyl, J.E. and Clayton, C. 2007).

Considerable research has been undertaken over the past decade to understand how leakage from a water distribution system reacts to pressure. It is generally accepted that flow from a hole in a pipe will react to pressure. In 1843, Torricelli developed a theoretical hydraulic model which proved that the flow rate of a liquid through a circular opening is proportional to the square root of the pressure head (Farley M. 2001; Thornton J. and Lambert A., 2005). This theorem can be mathematically expressed under the orifice equation 1.1 as follows (Lambert, 2001):

$$Q = C_d A \sqrt{2gh} \tag{1.1}$$

Where;
$Q =$ flow rate
$C_d =$ discharge coefficient
$A =$ area
$g =$ acceleration due to gravity
$h =$ the pressure head at the orifice.

An investigation was carried out on discrete Rand Water pipelines, among many causes of leakages includes vandalism on most air valves and gate valves, aging infrastructure, damages due to excavations by other service providers, corrosion due to external conditions such as power lines, railways and corrosive soil conditions, ground movements due to sinkholes, depth of pipe installation, water hammers, unsuitable pipe material for the soil conditions and poor pipe joints (lead caulked joint). The loss of pipe material due to corrosion on unprotected steel pipeline is illustrated in figure 2 below:

FIGURE 2: *Loss of pipe material due to corrosion (Rand Water Photographs)*

This paper presents the results obtained after using innovative method of leak detection and leakage management. This was achieved by performing leak detection using several technologies in discrete Rand Water pipelines. The structure of this paper consists of causes of leak in water distribution network, leak detection technologies used at Rand Water, strategies used to reduce water losses and results, followed by conclusion and recommendations.

2. CAUSES OF LEAKAGE IN WATER DISRIBUTION NETWORK

Previous investigations have reported that the causes of leaks in water distribution systems have been practically a huge worldwide concern to be overcome, because of the aging of water infrastructures (valves and pipelines) which leads to water loss through leakage (Schouten, M. and Halim, R.D. 2010). Saghi and Aval, investigated the causes of leaks in water distribution systems. The result of this study describes in detail the causes of leaks. There are many causes that are involved in the water leakage and these causes must be well understood to minimise water losses through leakages in water distribution systems (Saghi H and Aval A. A, 2015; Gupta A.D and Kulat K 2017).

Below is a further discussion of the causes of water leakages that were previously described in the paragraph 2 (Introduction & Background):

2.1 The material of the pipes

One of the factors in water leakage is the material of the pipes. Greyvenstein and Van Zyl (2007), conducted an experimental investigation into pressure and leakage relationship on some failed water pipes in Johannesburg (Greyvenstein, B. and Van Zyl, J.E. 2007). The results of this investigation showed that the effect of the pipe material plays a major role in the behaviour of individual leaks. Due to the material properties, pipes of different materials will fail differently. For instance, asbestos cement pipes will typically fail with longitudinal cracks, while steel and cast-iron pipes may leak through corrosion holes (Greyvenstein, B. and Van Zyl, J.E. 2007). In a finite element investigation on the behaviour of holes and fractures in several pipe materials (uPVC, cast iron, steel, and asbestos cement) under two loading states, Cassa et al further proved that leak area varies linearly with pressure (Cassa et al., 2010). According to hydrostatic pressure testing of HDPE pipe, the generic stages of pipe failure include failure due to a purely mechanical failure mechanism caused by ductile overload of the material, and failure due to a mechanical mechanism which manifests as non-ductile slit or pinhole cracks in the pipe wall, allowing leakage from the pipe (L.J Broutman et al., 1989 and W. Gedde et al., 1994).

2.2 The age of the pipes

Leakage is directly or indirectly affected by the age of pipes. This means that older pipes are more susceptible to leaks especially when pressure is high, this is because the wall thickness of a pipe reduces as the pipe ages. Putting in place a programme that can be scheduled with a timetable to rebuild the pipelines with different quantities will decrease water losses. Based on the experiments, which have been done, it is important to take into consideration the lifespan of the pipes, in terms of the pipe material. For instance, the recommended time for galvanized pipe is 15 years, polyethylene is about 16 years and 65 years for steel pipes (Saghi H and Ansariaval A. 2015). Studies of recent years show that with the increasing of the pipes age, the loss can reach up to 50% of the system input volume of water into the networks (Schouten, M. and Halim, R.D. 2010).

2.3 The diameter of the pipes

The diameter of the pipes is one the effective element in the rate of causes of leaks. The diameter of the pipes has direct impact on the hydraulic pressure which decreases when the diameter increases, resulting in the decrease of water leakage. However, using big diameter pipes involves more cost, this investment is more benefit, because it may reduce the loss of leaking water in a long-term program (Tabesh, M. and Honari, R. 2002).

In addition, the bigger the diameter of the pipe, the thicker of the shell of the pipe has. This case has as an advantage in terms of the stiffness of the pipe which increases and subsequently, increases the resistant of the pipe to internal and external pressures, as well as external loading which can lead to the pipe buckling when the performance limit of the pipe is exceeded (Saghi H and Ansariaval A. 2015; Tabesh, M. and Honari, R. 2002).

2.4 The pressure

The pressure is the common factor and hydraulic parameter with high importance, which determines the performance condition and the servicing of water supply system network. High pressure causes the increasing of leaks, and the number of the breakages in the network (Nazif, S., et al 2021; Collins, R. and Boxall, J. 2013). On the contrary, low pressure in the network causes the inability of complete supplying water or result in providing unsuitable water. Because of these two reasons, the design pressure must be adequate to overcome the static pressure and friction losses to satisfy the demand (Van Zyl, J.E. and Clayton, C. 2007). The pressure also should be effective for the stability and the structure of the system.

With high pressure, the probability of the pipe bursts and the crack of the system increase and the stability performance and suitable repairs of the network endangered (Thornton J. and Lambert A,2005). Therefore, it always important to know the pressure variations in the network. It is necessary to monitor the pressure in the network because the water loss might be caused by the network pressure conditions that changes uncontrollably. Particularly, the existing cracks within pipes will open with the high pressure and close with the low pressure (Saghi H and Ansariaval A. 2015).

2.5 Movement of the ground around the pipe

Movement of the ground may be caused by the sliding of the ground or shaking of the earthquake. This movement may subsequently result in sinkholes (especially in dolomitic grounds), which cause too much pressure on the pipes and resulting in cracks in the pipe, gaps between pipe joints, because the movement of the ground trying to separate the pipe joints, and this may eventually result in breaking of pipes (Saghi H and Ansariaval A. 2015).

2.6 The Corrosion of soil and ground condition around the pipe

The corrosion of the environmental soil and ground condition around the pipe material are inevitable, especially for buried pipes and joints made of metal, which attack the pipe material and causes leaks due to pipe corrosion, corrosive soil conditions affect the strength of the pipe material, especially for metal pipes.

It must be noted that corrosion has a very negative effect on the pipe integrity and lifespan of the pipe material, as it removes the material from steel pipes, thus reducing pipe wall thickness and creating leaks, which results in reduction of strength on the pipe wall over time (Saghi H and Ansariaval A. 2015).

2.7 Damages due to work activities, vibration, and road traffic loading

The damages caused by work activities on top of pipeline servitudes are also common because most of the water supply system network goes under the streets of the cities. In most cases water distribution network is buried underground along the roads with other services such as gas, electricity and communication network cables.

In the case of excavations by the other organisations such as gas, electricity and communications, these activities may damage the pipes, which will result in leakage and an increase in water loses. Excessive, pressure due to vibration (sine waves) and road traffic loading on the pipeline will eventually damage the pipeline, if the loading force exceeds the limits of the performance of the pipe material, this will cause a bending and therefore failure due to buckling of the pipe (Saghi H and Ansariaval A. 2015).

2.8 Water hammer effect

Water hammer effect is also one of the causes of leaks in the water network. Water hammer has the potential to damage joints, fittings, and connections, resulting in poor seals and ultimately leaky pipes. This effect makes some quicks waves and moves fast, which may subsequently result in transient pressures that can eventually damage the pipeline (Danshfraz, R and Moradi, N 2012). It is therefore important to take into consideration of the water hammer effect during the pipeline design projects to prevent damages in the pipelines (Saghi H and Ansariaval A. 2015).

2.9 The Climate Conditions

The climate conditions are one of the cause of leaks, because due the change of temperatures, the pipe material changes its structural integrity in terms of strength. When the temperature is high, the strength of the pipe material decreases, especially for pipes made of plastic and polyethylene components.

In addition, when the depth is not suitable, and the coverage is not enough, the effect of the quality of the soil together with the rainy conditions and the low temperature may cause freezing. This freezing causes tension on the pipes and results in cracking (longitudinally and circumferentially) of pipes and consequently results in leakage (Saghi H and Ansariaval A. 2015).

2.10 The Depth of placement of the pipes

The depth of the placement of the pipes in the ground and traffic loading pressure are causes of leakage. The depth at which the pipe pipeline is laid has a significance role in the leakage rate in distribution system. External pressures from traffic loadings impact the pipe joints, as well as the pipeline which can be affected by a buckling once the performance limit of the pipe is exceeded. This is likely to happen when pipe is laid at a shallow depth (Saghi H and Ansariaval A. 2015).

2.11 Poor-quality in construction of the pipelines

The poor-quality during construction leads to incorrect installation of the pipelines and these are causes of leaks. The installation performed by unskilled workers together with lack of supervision, poor welding or using non-standardised techniques may result in poor sealing of the joints. It is important to conduct hydraulic pressure testing after the construction of a newly installed pipelines, to ensure proper joints sealing before the commission (Saghi H and Ansariaval A. 2015).

2.12 Using inappropriate materials for the base and coverage of the pipes

During the installation of pipes, care must be taken in ensuring that appropriate material is used for the bedding and blanket around the pipe. Because of this, the surrounding of pipes should be made so that a good base is prepared for the settling of the pipes to prevent the extra tensions from being transmitted to the pipes. When inappropriate materials (such as that with large stones) are used, unbalance pressures are applied to the pipes and damage them, depending on the pipe material (Saghi H and Ansariaval A. 2015).

2.13 Water Quality and Corrosive Waters

Water flowing inside the pipe should not be corrosive. Corrosive waters cause corrosion and weaken the pipes. Corrosion occurs from erosion of the pipe material, until tiny holes which will be developed over time and become big leaks (Saghi H and Ansariaval A. 2015).

3. DIFFERENT LEAK DETECTION TECHNOLOGIES USED AT RAND WATER PIPELINES NETWORK

The following leak detection technologies were used to detect leaks on water pipelines at Rand Water:

3.1 Sahara Technology

Sahara leak detection technology consists of acoustic device that is a tethered inline leak detection technology; it is also used as an intrusive method of leak detection that isolates and approximate the leak size and air pockets in minimum pipe diameters of 300mm and above for all pipeline material. The technology is based on principle of acoustics, leaks are detected in real time with the accuracy of less than 1.0m on surface location. A minimum of 50mm opening is required for an insertion of the system.

This is generally done through an air valve on top of the pipe. The tethered head sensor travels through the pipe with the flow of water for a maximum distance of 2.0km per survey, which is limited by the length of the rope. The position of a leak is pinpointed and segregated on the surface in real time (Rand Water Sahara Leak Detection Inspection Report 2016).

3.2 SmartBall Technology

SmartBall leak detection technology consists of sophisticated acoustic leak detection circuity and is released untethered into the water flow of a pipeline through an air valve. The Smartball follows the water flow and rolls at the bottom of the pipeline continuously recording the acoustic activities in the pipeline. The system is very sensitive to the sound made by changes in pressure and, any pressure variations between inside and outside of the pipeline will be detected regardless of the pipe material. The SmartBall is inserted inside the pipe through an air valve at upstream. At downstream there is a retrieval point, which is a designed extraction net to capture the rolling ball and extract it from the pipeline through an air valve. A single deployment can be more than 20km, this is limited by the lifespan of the batteries. Data is analysed through a computer to determine the location of leak on an approximate distance of 1.0m (Rand Water Report: Emergency Pipeline Inspection Using Smartball 2022).

3.3 Piper Technology

Piper leak detection technology is an untethered ball consisting of acoustic leak detection sensors. When travelling inside the pipeline, Piper device continuously records a comparatively low flow noise, creating a baseline for the measured sound intensity. In pressurised pipelines, the jet of liquid passing through the crack or hole creates a noticeable sound or characteristics of a rushing sound that exceeds the baseline noise in a localised region around the leak. Conversely, if there is no change in the average sound intensity along the length of a pipeline, no leaks are detected. The piper is designed to travel at the centre of the pipeline whilst the Smartball rolls at the bottom of the pipeline. The Piper is able to cover a distance of 60-80m at a single deployment. This distance in deployment is limited by the battery life span which is 48 hours. Like the SmartBall, the piper ball is inserted through an air-valve inside the pipe at upstream and it is retrieved at downstream using a designed net. (Rand Water Emergency Leak Detection Report: Piper 2021).

3.4 Satellite Leak Detection Technology

Satellite leak detection is one of the new technologies used to identify leaks using artificial intelligence (AI). The technology consists of studying the spectral imageries captured by satellite and examine them with the use of specialised algorithms. This technology is non-intrusive, non-destructive and non-disruptive. In addition, this technology guarantees a survey of a large area of water pipeline network monitoring and identification of leakages and potential leakages. Satellite leak detection is indicative because it requires a complementary technology to pinpoint leaks on the ground. The use of acoustic correlators was used in Rand Water to pinpoint leaks on the ground (Rand Water Satellite Leak Detection Report 2021).

4. STRATEGY USED TO REDUCE WATER LOSS AND RESULTS

Rand Water has currently move in new strategic objectives include reducing water losses and increasing operational efficiency using new, innovative, and efficient methods of leak detection that are non-intrusive to the pipeline and non-disruptive to the on-going operations. The organisation also uses the available and efficient technology to monitor the wall thickness on pipelines, as a proactive measure in order to plan for the necessary repairs and refurbishments to prevent the leaks from occurring and preserve the integrity of the pipeline assets.

To reduce Non-Revenue Water, Rand Water lodged on extensive leak detection and repair program on its pipeline network. Various leak detection technologies were used to detect leaks in Rand Water pipelines. Some of these technologies were used in combination as they complement each other (Rand Water Emergency Leak Detection Report: Piper 2021).

The results of different above-mentioned technologies used by Rand Water for condition assessment and leak detection will enable the organisation to reduce the NRW by 3%. Which will reduce the amount of water loss from 349 000kl/Day to 149 000kl/Day of the total volume supplied per day. Table 1 below display the current NRW per year and the target (Rand Water Annual Report 2021).

TABLE 1: *The current percentage of NRW at Rand Water and target (Rand Water Annual Report 2021).*

Rand Benefit on Distribution	
Current Annual NRW	7.0%
NRW Target	3.0%
NRW Volume @7%	349 000kl/day
NRW Reduction Target Volume @3%	149 500kl/day
Volume of NRW Savings on Re-paired Leaks	199 500kl/day

Where: R = Rand
kl = kilolitre
NRW = Non-Revenue Water

Table 2 below illustrates the profit that the organisation could make annually when the detected leaks are repaired (Rand Water Annual Report 2021).

TABLE 2: *Annual profit on repaired leaks (Rand Water Annual Report 2021).*

Profit on Repaired Leaks	
Cost of sale	R11.62/kl
NRW @7%	R1 480 213 700.00
NRW @3%	R618 439 640.00
NRW Savings on Repaired Leaks	R846 139 350.00

Where: R = Rand
kl = kilolitre
NRW = Non-Revenue Water

CONCLUSION

The combination use of various complementary leak detection technologies to detect leaks on portable water pipelines at Rand Water has been confirmed to be successful. Results and observations from these various technologies have delivered expected results, meeting the objectives for a successful leak detection at Rand Water. The results indicated that the leak detection technologies were useful in dealing with the aging infrastructures and water loss resulting from pipeline leakage.

Proactive measures can be used to prevent leaks and burst on full scale, these involve the use of technologies such as Magnetic Tomography Memory and Long Range Guided ultrasonic to determine the pipe wall thickness. In addition, an adequate pipeline protection such as cathodic protection should also be installed in the network to protect steel pipelines against corrosion. Pipeline condition assessment using External Current Direct Assessment (ECDA) and Internal Current Direct Assessment (ICDA) will work as effective maintenance strategy on the existing pipelines.

These leak detection technologies and appropriate maintenance procedure mentioned above will afford Rand Water an opportunity to be proactive in managing leakages. Pipeline rehabilitation or replacement of pipe section could be performed without having to wait for leaks to surface. A global view of the general outlook of leakage on the Rand

Water pipeline network could be achieved (Rand Water Emergency Leak Detection Report: Piper 2021).

In consideration of the cost associated with sourcing of raw water, purification, pumping and supply of portable water, implementation of leak detection programme using leak detection technologies on permanent basis, and the condition assessment strategies could save the organization up to 199 500 kiloliters per day of NRW and that translates to profit of more than R846million annually (Rand Water Annual Report 2021).

5. RECOMMENDATIONS

Based on the above results, it is recommended that Rand Water should put in place a programme of leak detection on permanent basis using relevant technologies to detect leaks, and permanently implement the relevant technologies to monitor pipe wall thickness and defects on pipelines to prevent burst on pipelines network. This programme should be followed by a repair programme to minimise water losses and preserve the pipeline integrity.

Large scale use and future deployment of these technologies should be implemented by Rand Water. Yearly schedules to scan the pipelines as preventive method should be implemented to monitor corrosion on pipelines and mechanical stress concentration in order to prevent leaks from occurring in water distribution network.

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