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Sepideh Yazdekhasti, Kalyan Ram Piratla, John C Matthews, Abdul Khan, Sez Atamturktur,

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Optimal selection of acosutic leak detection techniques for water pipelines using multi-criteria decision analysis

ABSTRACT

Purpose: There has been a sustained interest over the past couple of decades in developing sophisticated leak detection techniques that are economical and reliable. Majority of current commercial leak detection techniques are acoustics-based and they are not equally suitable to all pipe materials and sizes. There is also limited knowledge on the comparative merits of such acoustics-based leak detection techniques (ALDTs). The purpose of this paper is to review six commercial ALDTs based on four decisive criteria and subsequently develop guidance for the optimal selection of an ALDT.

Practical implications: The study approach and the findings will have a broad impact on the water utility industry by identifying a suite of suitable ALDTs for a range of typical application scenarios. The evaluated ALDTs include listening devices, noise loggers, leak-noise correlators, free swimming acoustic, tethered acoustic, and acoustic emissions. The evaluation criteria include cost, reliability, access requirements, and the ability to quantify leakage severity. The guidance presented in this paper will support efficient decision making in water utility management to minimize pipeline leakage.

Methodology/approach: Numerous publications and field demonstration reports are reviewed for evaluating the performance of various ALDTs in this study to inform their optimal selection using an integrated multi-criteria decision analysis framework. The findings are validated using interviews of water utility experts.

Originality/value: This study attempts to address the problem of severe dearth of performance data for pipeline inspection techniques. Performance data reported in the published literature on various ALDTs is appropriately aggregated and compared using a multi-criteria decision analysis, while the uncertainty in performance data is addressed using the Monte-Carlo simulation approach.

Key Words: Water sustainability, leak detection, pipeline inspection techniques

1. INTRODUCTION

Domestic and industrial demand for water is increasing rapidly around the world, while the freshwater resources are becoming increasingly scarce. Currently, the water distribution infrastructure is critically deteriorated leading to significant leakage of treated water, making this supply-demand imbalance worse. It is estimated that roughly 7 billion gallons (≈ 15-25%) of treated water is lost per day in the U.S. (ASCE, 2013), and this problem is worse in some developing and under-developed countries (Abdel Khaleq and Dziegielewski, 2006; Thornton et al., 2008). Leakages of such magnitude are not sustainable as water supply (i.e., collection, treatment and distribution of water) is energy-intensive and expensive undertaking (Misra and Malhotra, 2011; Hendrickson and Horvath, 2014). Leaks can also potentially compromise water quality, resulting in contaminant infiltration, leading to health issues (Martini et al., 2015). In an attempt to address this serious problem, numerous leak detection techniques (LDTs), ranging from simple visual inspection to sophisticated acoustics-based ones, have been investigated hitherto.

Previous studies reviewed various LDTs and highlighted their specific advantages, limitations and suitability to different application scenarios. While a majority of these studies focused on LDTs in general (Costello et al., 2007; Colombo et al., 2009; Thomson and Wang, 2009; Ahadi and Bakhtiar, 2010; Puust et al., 2010; Liu et al., 2012; Liu and Kleiner; 2012 and

2013; Cataldo et al., 2014; Xu et al., 2014; Deepak et al., 2016; Atef et al., 2016; Abdulshaheed et al., 2017), some specifically focused on acoustics-based techniques (Nestleroth et al., 2012; Hunaidi, 2012; Ismail et al., 2014; Anguiano et al., 2016; Martini et al., 2016). The acoustics-based LDTs (hereafter referred as ALDTs), which are widely used in practice, rely on the premise that a leak induces noise or a vibration signal that travels through the pipe wall or the water column and that this signal can be detected using appropriate sensing equipment. Although ALDTs have worked well in the cases of small to medium-diameter (< 300 mm) metallic pipelines, their suitability to plastic and large-diameter metallic pipelines has been uncertain, owing mainly to the possibility of high signal attenuation rate in these types of pipelines (Hunaidi, 2012).

Innovative advancements in the recent past reportedly improved the suitability of ALDTs to plastic and large-diameter metallic pipelines through the passage of sensors inside the pipeline via a tether or by freely swimming (Nestleroth et al., 2012). Although such advancements complement existing techniques, they are still not suitable for all types of pipe materials, geometries, and environments. Furthermore, choosing an appropriate technique from the various conventional and latest technologies under various operating conditions is a challenging task (Deepak et al., 2016). This paper is focused on the review of several ALDTs and their comparison, after taking into account the recent technological developments, based on the following criteria: cost (C_C), reliability (C_R), ability to determine leak severity (C_Q), and pipe access requirements (C_A). The criteria employed in the study are those reported to be influential based on the literature review and discussions with water utility experts. The comparative evaluation of ALDTs is then leveraged for determining their relative suitability to typical application scenarios using Monte-Carlo Multi-criteria Decision Analysis (MCMCDA) approach.

Multi-criteria decision analysis technique (MCDA) is a popular technique used in various disciplines for complex decision-making problems (Fishburn, 1967; Kiker et al., 2005; Wang et al., 2009; Ho et al., 2010; Cinelli et al., 2014; Govindan et al., 2015). MCDA facilitates decision making through the way people think by evaluating possible decisions based on multiple criteria to determine the most suitable one (Najafi and Bhattachar, 2011). Although MCDA technique has been widely used in other disciplines, it has not been adequately employed for choosing technologies in water utility industry, owing mainly to the complex nature of the problem combined with ever-evolving technologies and lack of data synthesizing their performance. The real-world selection of leak detection techniques is often influenced by multiple criteria that may not be quantitatively comparable. Moreover, it is difficult to determine stakeholder preferences for the various criteria involved in the process of using conventional MCDA. Therefore, the conventional MCDA approach is integrated with an uncertainty quantification approach through Monte-Carlo simulation in this study for developing optimal ALDT selection preferences (Madani and Lund, 2011; Durbach and Stewart, 2012). The performance of various ALDTs based on the chosen decision criteria is synthesized from literature and the study outcomes are validated using interviews with water utility professionals.

Overall, this paper offers a synthesis of performance of various ALDTs and subsequently provides guidance to water utility owners in selecting ALDTs for optimal leakage surveys.

2. REVIEW OF ALDT OPTIONS FOR WATER PIPELINES

Leakage detection methods cover a wide spectrum of techniques that leverage various scientific principles. Table 1 categorizes several popular pipeline inspection techniques into acoustic and non-acoustic classes based on whether or not acoustic principles are employed in their operations. Non-acoustic techniques are further classified into direct (Amirrato and Zayicek, 1999; Shin et al., 2009; Tse and Wang, 2009; Agarwal, 2010; Hao et al., 2012; Liu and Kleiner, 2013; Khader, 2016) and indirect methods (Sadiq et al., 2004; Colombo et al., 2009) based on whether or not they directly indicate leakage presence without needing to further interpret the results through inferential indicators (Liu and Kleiner, 2013).

The acoustic techniques, as shown in Table 1, are also categorized in two groups based on their capabilities. The first group of techniques, which comprises listening devices, noise loggers, and leak-noise correlators, are capable of only leak detection and/or locating. The second group of techniques, which comprises free swimming or tethered sensors and acoustic emissions, are capable of assessing the structural condition of the pipeline in addition to leak detection and/or locating. The acoustic techniques focused on leakage detection are briefly described in this section.

2.1 Listening Devices (LD)

Listening technique is a commercial leak-detection method that has been used since 1850s (Pilcher, 2003). This technique, which is depicted in Figure 1a, enables leakage detection through fire hydrants or valves by listening to the sound of water emitting from the leak using inexpensive listening rods or hydrophones. LD is not highly reliable for detecting small leaks unless further inspection is carried out to ensure leak-induced signals are not masked by ambient noises. Piezoelectric materials, adjustable amplifiers, and noise filters are used along with the listening rods and hydrophones for filtering the ambient noises depending on the frequency range of interest (Hunaidi et al., 2000). Sound-based transducers, such as ground microphones, are also capable of detecting leak-induced sound at ground level in addition to monitoring valves or fire hydrants.

The accuracy of the LD technique reportedly decreased with increased cover depth, increased distance between the leak and monitoring location, decreased conductivity of soil, decreased pressure of fluid in the pipe, and increased temperature (Hunaidi et al., 2000). The accuracy of LD technique is also uncertain in large diameter metallic and plastic pipelines, for they exhibit higher acoustic attenuation rate (Hunaidi, 2012); for example, the acoustic attenuation rate in plastic pipelines is five times greater than that in metallic pipelines (Hunaidi et al., 2000). The set-up time of LD equipment to be attached to a hydrant or valve is estimated to be about five minutes, whereas its average on-station time is estimated to be in the range of two to five minutes depending on the operator's familiarity with leakage-induced sounds in pipeline systems (EPA, 2010). The applications, advantages, and limitations of the LD technique are highlighted in Table 2.

2.2 Noise Loggers (NL)

Noise logger is an ALDT that has been commercially available since 1990s. Noise loggers, as depicted in Figure 1b, can be embedded in a pipeline system permanently or temporarily (at least for two consecutive nights typically), and are programmed to listen for leaks. Statistical analysis of the recorded data, especially the noise intensity and consistency, over a period enables the detection of the likely presence of a leak. As soon as a suspected leak is detected, an alarm state is initiated through a radio signal to indicate the presence of a leak. Unlike manual techniques such as LD, which can be used only in an ad-hoc manner, NL can be installed for permanent use.

Furthermore, it is a suitable option for busily crowded areas where manual surveys might be difficult to carry out. The suggested distance of loggers from each other in NL technique is 100 m for metallic (of diameter ≤ 400 mm) and 50 m for plastic pipelines (Covas et al., 2006). The set-up time for NL technique is estimated to be in the range of 20 to 30 minutes per logger with limited training required for the technician. On the other hand, additional time of a trained professional is required for analyzing the gathered data after a reasonable period of monitoring time (EPA, 2010). The applications, advantages, and limitations of NL technique are further highlighted in Table 2.

2.3 Leak Noise Correlators (LNC)

LNCs are commercial ALDTs that have been in use since 1978 primarily for pinpointing leaks upon determining their presence and approximate vicinity. LNC technique entails using either accelerometers or hydrophones attached at two contact points on the pipeline surrounding the leak, as depicted in Figure 1c. The correlation between signals at the two contact points is leveraged to estimate the location of a potential leak. Hydrophones are preferred for locating small leaks, when placed closely to the leak (< 4.5 m) (Hunaidi, 1999), and they are also generally more suitable for plastic pipelines (Thomson and Wang, 2009). With the use of hydrophones spaced at 100 m from each other, LNC technique is reportedly estimated to inspect 3 km of pipeline per day with a two-person crew (Hunaidi, 2012). On the other hand, accelerometers are preferred for metallic pipes, especially small diameter ones (< 300 mm) when employing LNC technique (Nestleroth et al., 2012; Hunaidi, 2012). With the use of accelerometers spaced at 200 m, LNC technique is reportedly estimated to inspect 9 km of pipeline per day with a two-person crew (Hunaidi, 2012). The background noise issues in plastic pipelines make it necessary to use appropriate digital filters to enhance accuracy with the LNC technique (Gao et al., 2004 and 2005; Brennan et al., 2008).

The set-up time for LNC technique is estimated to be in the range of 10 to 20 minutes per station, whereas the average on-station time is estimated to be in the range of 30-60 minutes or more depending on the time of the day (EPA, 2010). Further applications, advantages, and limitations of LNC technique are highlighted in in Table 2.

2.4 Free Swimming Acoustics (FSA)

FSA is an ALDT that is commercially available since 2004. The FSA technique, which is depicted in Figure 1d, is mainly comprised of a free-swimming foam ball with an instrumented-filled aluminum alloy core and it is suitable for pipelines of diameter 250 mm or larger. This technique works through the passage of the free-swimming ball directly adjacent to the source of noise (Liu et al., 2012) and consequently, it is more suitable for highly attenuating pipelines such as those made of plastic in comparison to the previously described ALDTs. FSA technique is also used for structural pipeline inspections in some applications. The core of the foam ball is approximately 60 mm in diameter and houses acoustic acquisition device, data storage equipment, and a power supply (Puust et al., 2010). The foam shell around the aluminum core, which helps in reducing the ambient noises in the pipeline environment, can vary in diameter depending on the project parameters including but not limited to pipe diameter, pressure, and configuration; and the shell’s spherical design allows for more flexibility in passing through small radius bends and obstacles. The FSA technique is deployed into the flow of a pipeline from a valve with clearance of at least 100 mm diameter, which then freely swims to a downstream extraction point. The frequency content of the recorded pipeline acoustic activity is evaluated to inform leakage detection. Specifically, the acoustic frequency and power can indicate the presence and severity of leaks by comparing the recorded data with leak calibration curves in the post-processing analysis. The accuracy of leak calibration curves will increase as more data points are added, since the leak indicator is a function of various field criteria such as pressure, pipe diameter, and pipeline configuration (Fletcher and Chandrasekaran, 2008). The FSA technique has detected leaks as small as 0.11 lit/min under ideal conditions and in pipelines with operational pressure more than 10 psi (Nestleroth et al., 2012). The device is also capable of sending out ultrasonic pulses every 3 seconds to track the position of the ball during the survey; or it can be tracked through GPS, which allows the location of leak to be determined with ±1 m precision (Fletcher and Chandrasekaran, 2008). The specific applications, advantages and limitations of FSA technique are highlighted in Table 2. It should be noted that the FSA technique struggles to discern leaks in clusters that are less than 0.8 m apart (Nestleroth et al., 2012); this limitation is however applicable to other ALDTs as well. The set-up time and on-station time of the FSA technique varies widely depending on the access and length of the pipeline to be inspected; the average set-up time is estimated to be about an hour (EPA, 2010).

2.5 Tethered Acoustics (TA)

TA is a commercially available technique that has been in use in the leak detection industry since the mid-1990s. This technique uses a hydrophone sensor, as depicted in Figure 1e, which is mounted at the end of a tether and travels inside a water main to record leak noises and in some cases conduct visual and structural inspections. TA technique, similar to FSA, takes advantage of passing directly adjacent to the leak and subsequently offers improved suitability for leak detection in plastic and large diameter metallic pipelines, compared to the external ALDTs. The TA system is deployed into the pipeline flow from any existing tap point that is at least 50 mm in diameter and connected to a pipeline of diameter larger than 250 mm. As the system passes a water leak, the sound is detected. The sensor is tethered to the ground level and an operator tracks the sensor from above ground in order to locate the position of detected leaks. The sensitivity of TA to leaks as small as 0.015 lit/min and its accuracy in locating leaks with less than ±1 m precision have been proven in field trials (Nestleroth et al., 2012). In the later versions of TA, a camera has been added to reveal more information on the pipeline condition; similarly, an assessment sensor for the pipe wall can be added for the inspection of metallic pipeline wall thickness. In addition to revealing average wall thicknesses at set intervals of a pipeline (every 9 m) based on the speed of sound (Liu and Kleiner, 2013), the TA system is capable of detecting internal corrosion, illegal taps, unknown laterals, and loss or damage to internal lining (Youngpyo and Boon, 2012).

The average set-up time for TA technique is estimated to be one hour; although it should be noted that this is highly dependent on the water main access. Furthermore, the average on-station time for TA technique is estimated to be in the range of one to three hours depending on the size and condition of the pipeline; the on-station time is expected to be more for older water mains, for it takes longer to map and characterize numerous leaks (EPA report, 2010). Further applications, advantages, and limitations of the TA technique are highlighted in Table 2.

2.6 Acoustic Emission (AE)

AE technique is a commercial technique for near real-time leak detection (Xu et al., 2012) and integrity inspection of concrete pipelines, especially large diameter ones (Liu et al, 2012). The two phenomena that guide AE technique are: (a) sensors can detect the energy waves which are produced by the pressurized fluid flowing from the leak, as depicted in Figure 1f; and (b) growth of local cracks, cavitation at the leak, and movement of soil and temporary entrapment of solid particles at the pipe opening due to the leak can be the other sources of generated acoustic waves which propagate through the pipeline material or the fluid (Pollock and Hsu, 1982). Different sensors such as hydrophones, piezoelectric, fiber optics and micro-electromechanical can be used with the AE technique using appropriate monitoring frequencies ranging between 10 KHz to 40 KHz (Liu et al, 2012). The maximum spacing of sensors with this technique is suggested to be 100 m to achieve sufficient resolution of recorded data (Anastasopoulos et al., 2009). Filtration of noises, such as those resulting from passing traffic, pumps, and ground movement, is necessary before the recorded data using this technique can be analyzed. The higher average of signal amplitude at sensors closer to the leak narrows down the potential leak location to a smaller area.

The estimated average set-up time for AE technique excluding the time required for excavation is about one hour, while its average on-station time is in the range of two or three hours (Karr et al., 2003). The applications of AE technique along with specific advantages and limitations are highlighted in Table 2.

3. COMPARATIVE EVALUATION OF ALDTs

The ALDTs are comparatively evaluated for their suitability to four typical application scenarios based on four criteria. This section describes the typical application scenarios, presents an overview of the four evaluation criteria, and summarizes the performance of ALDTs

3.1 Application Scenarios

The four broad application scenarios considered in this study are identified in Table 3. Scenarios one (SC1) and two (SC2) represents small diameter (< 300 mm) and large diameter (≥ 300 mm) metallic pipelines, respectively. A majority of water pipelines that are currently in service fall under either SC1 or SC2 scenarios. Scenario three (SC3) represents small diameter plastic pipelines (< 300 mm) which are becoming increasingly popular for water applications (Liu et al, 2012). Scenario four (SC4) represents large diameter concrete pipelines (> 600 mm) which are often used in transmission applications. Table 3 also identifies the set of ALDTs that are generally reported to be suitable for each application scenario.

3.2 Performance Evaluation

The four evaluation criteria employed for the comparative analysis of ALDTs are selected based on the review of literature (Misiunas, 2008; Puust et al., 2010; Thuruthy, 2012) and discussions with water utility professionals. Those criteria are described in this section.3.2.1 Reliability (C_R): Reliability in this context signifies the trustworthiness of the inspection results and it can be interpreted as the probability of detecting a leak and differentiating it from the ambient noises in a water pipeline system without any false-positives or false-negatives. This criterion is considered dependent on the sources of possible errors and likelihood of false positive/negative alarms with the use of any ALDT. The sources of errors with each ALDT have been highlighted in section 2. In order to estimate the likelihood of false alarms, the past performance of ALDTs has been synthesized from various field demonstration reports and other documents published by water utilities and researchers (Hunaidi et al., 2000, 2004, and 2012; Dingus et al., 2002; Van der Kleij and Stephenson, 2002; Colla et al., 2003; Hunaidi et al., 2004, Hunaidi, 2012; Hunaidi and Wang, 2006; Gao et al., 2004; Chastain-Howley, 2005; Mergelas and Henrich, 2005; Sánchez et al., 2005; Suzuki et al., 2005; Covas et al., 2006; Stringer et al., 2007; Fletcher and Chandrasekaran, 2008; Misiunas, 2008; Anastasopoulos et al., 2009; Thomson and Wang, 2009; Hamilton, 2009; Nestleroth et al., 2012; Nuss et al., 2012; Xu et al., 2012; Davis et al., 2013; Hamilton and Charalambous, 2013; Anguiano et al., 2016). Based on the synthesis of past performance of various ALDTs, they are categorized qualitatively into low, moderate and high reliability classes for each application scenario, as shown in Tables 4 and 5. Table 4 presents quantitative performance scores of ALDTs for various criteria as a translation of the qualitative performances reported in the literature. Table 5 presents performance scores for various application scenarios depending on the suitability of ALDTs. Techniques that fall into the low reliability category, with a score of 1 (see Table 4) have been reported to generate high rates of false alarms in the field demonstrations. In contrast, techniques that fall in the high-reliability category, with score of 3, usually produced accurate results in the field demonstrations. Techniques that lacked consistency in performance but have been reported to be more satisfactory than the techniques in the low-reliability category are grouped into the moderate-reliability category with a score of 2. The ALDT performance scores presented in Tables 4 and 5 are derived assuming that the ALDTs are used in an ad-hoc (or temporary) manner and not in a permanent deployment manner. It should also be noted that the scores of ALDTs vary depending on the application scenario because some ALDTs are more suitable to certain types of pipelines than others are. For example, the score of LNC for C_R criterion is higher in SC1 than SC2 and SC3, because of its better suitability to small diameter metallic pipelines (SC1). The latest improvements in LNC technique enabled by the enhanced correlation function, which improves the detection of peaks in case of narrow-band leak-induced signals, make it a more reliable ALDT for small diameter metallic pipes than other pipeline categories.

3.2.2 Ability to Quantify Leak Severity (C_Q): ALDTs vary in their respective capabilities to quantify leak severity information that is vital for intervention planning by utility operators.

Techniques that are incapable of quantifying leak severity are grouped into the "Incapable" category with score of 1 as shown in Table 4, while the capable techniques are grouped into the "Capable" category with score of 3. ALDTs that either provide less accurate leak severity information or need additional calibration for greater accuracy are grouped into the "Somewhat capable" category with a score of 2. The performance scores of various suitable ALDTs based on C_Q criterion for the four application scenarios are presented in Table 5. It can be observed from Table 5 that only FSA and TA are rated as "Somewhat capable" of determining leakage severity due to the possibility of comparing the recorded data from leakage surveys with the leak calibration curves. Most state-of-the-art ALDTs are incapable of accurately determining severity information, except for the ones that are typically employed for a more comprehensive pipeline condition assessment (e.g., Impact Echo). Such condition assessment techniques are excluded from this study which solely focuses on leak detection techniques.

3.2.3 Pipeline Access Requirements (C_A): Different ALDTs have varying pipeline access requirements, as discussed in section 2, and they are accordingly grouped into three categories as shown in Table 4 and appropriately rated for the four application scenarios as shown in Table 5. ALDTs that require access to the surface of the buried pipeline, which is inconvenient to the utility operator and therefore less preferred, are grouped into the "Pipeline surface" category with a score of 1. As can be seen from Table 5, AE technique, which requires access to the pipeline surface all along the length of inspection, is given a score of 1. On the other hand, ALDTs that can conveniently tap into above ground fixtures such as fire hydrants are grouped into the "Above ground" category with a score of 3. As can be seen from Table 5, LD, NL and LNC techniques, which tap into aboveground fixtures, are given a score of 3. The inline ALDTs that work through the movement of transducers inside the pipeline require two access points, one for their insertion and another for extraction, and these ALDTs are grouped into the "Insertion and extraction only" category with score of 2. A few ALDTs can be classified into more than one category but with varying reliabilities; for example, LNC can work through "Pipeline surface" as well as "Above ground," but tapping the fire hydrants (Above ground) was reportedly more accurate (Hunaidi, 2012). Similarly, LD can work through "Above ground" as well as through manual inspection, but "Above ground" category was reportedly more accurate (Hunaidi et al., 2000).

3.2.4 Cost (C_C): Based on the total cost incurred in inspecting a unit length of pipeline, ALDTs are categorized into three groups namely, high, moderate, and low with corresponding performance scores of 1, 2 and 3, respectively as shown in Table 4. The total cost, which is subjectively compared for various ALDTs, comprises of costs associated with labor, equipment, data analysis, and the societal inconvenience resulting from their use. The cost information used for the comparison of ALDT performance is obtained from the published literature.

The equipment cost is a function of the hardware and software needs of an ALDT. For the reasons highlighted in section 2, LD works with hardware that is cheaper than that of FSA, TA, and AE. Similarly, hardware costs of correlator-based techniques such as LNC are high except for those that can work with personal computers instead of existing expensive commercial correlators (Hunaidi et al., 2004). Labor costs, on the other hand, are dependent on the set-up requirements of each ALDT and the time it takes to inspect a unit length of a pipeline. Labor costs for setting-up tend to be higher if access to the external surface of the pipeline is desired. Consequently, labor costs for AE, which requires external pipeline surface access, would be more than other techniques. Other techniques including LD, NL, and LNC cost less in terms of labor. LD technique, which tends to take more time for inspection due to its less sensitive sensors compared to NL and LNC, would therefore require shorter sensor-to-sensor spacing, which in turn results in higher inspection-related labor costs followed by NL and LNC. On the other hand, FSA and TA techniques, which require only two access points (as insertion and extraction), would be least expensive for longer lengths of inspection due to minimal inspection time per unit length of the pipeline. The cost of analyzing the inspection data depends on the ease of analysis in terms of expertise required to translate the data into a more comprehensible format for interpretation. Data analysis for LNC, FSA, and AE techniques would be relatively more expensive due to the complexity involved in interpreting the inspection data.

In summary, scores of ALDTs in terms of C_C are based on their combined performance for all the afore-described cost categories coupled with limited quantitative and qualitative data available in the literature (Karr et al., 2003; Chastain-Howley 2005; Stringer et al., 2007; Thomson and Wang, 2009; EPA, 2010; Nestleroth et al., 2012 and Xu et al., 2012). The ALDTs are subsequently rated based on cost for the four application scenarios as shown in Table 5. It is found that LD is the only technique that can be grouped into the ”low” category for C_C, for it has cheaper needs in majority of cost categories and it does not result in any societal inconvenience. All other ALDTs are grouped into either “moderate” or “high” categories for C_C, as can be seen in Table 5. It should also be noted that the score of FSA for C_C criterion is lower in small diameter pipelines (i.e., SC1 and SC3) than large ones (i.e., in SC2 and SC4), as FSA is relatively more expensive for smaller diameter pipes due to the additional effort required to gain internal access.

4. DECISION-GUIDANCE FOR OPTIMAL ALDT SELECTION

Monte-Carlo multi-criteria decision analysis (MCMCDA)-based guidance is proposed for determining selection preferences of ALDTs for the typical application scenarios. This section presents an overview of the MCMCDA framework and the results of selection preferences.

4.1 Decision-making Framework

In order to identify an optimal ALDT for a given set of user-defined criteria preferences, a MATLAB code is written to integrate Monte Carlo analysis with the multi-criteria decision analysis (MCDA) approach. Typical MCDA procedure breaks down a decision problem, with precisely identified influential criteria, to a hierarchical form. Subsequently, the set of choices are evaluated based on each criterion while the decision criteria themselves are evaluated to obtain percentage weightings (Saaty, 1987). In a traditional MCDA procedure, the user (i.e., the decision maker) determines the relative criteria weightings. Due to the wide range of application scenarios and individual preferences, it is challenging to derive one set of representative criteria weightings. To address this inherent uncertainty with criteria weightings, Monte-Carlo simulation approach is adopted. Successful performance of integrated Monte Carlo-MCDA procedures have been reported in various probabilistic judgments applications (Banuelas and Antony, 2004; Vaidya and Kumar, 2006; Jing et al., 2012; Vien and Toussaint, 2015). In the MCMCDA procedure, the criteria percentage weightings will be randomly generated so that they add up to 100%, and the decision problem is solved numerous times (i.e., simulations) using various sets of random criteria weightings (Banuelas and Antony, 2004). The MCMCDA algorithm is graphically illustrated in Figure 2.

Furthermore, the MCMCDA procedure is adjusted to reflect the prevalent biases in the water utility decision-making. The importance weighting of each decision criterion would need to be tailored for every project based on the budgetary constraints, risk tolerance and overall service level objectives. However, in an attempt to study a wide range of situations, twenty seven "what-if" cases have been developed for each of the application scenarios (i.e., SC1-SC4) using systematic variation of criteria percentage weightings, as shown in Figures 3, 4, 5 and 6. As per the discussions with water utility experts, as well as reviewing the published research articles and field demonstration reports (Misiunas, 2008; Puust et al., 2010; Thuruthy, 2012; Davis et al., 2013; Macey et al., 2014), cost, access requirements, and reliability are believed to be much more influential in real-world decision making compared to the criterion pertaining the ability to quantify damage severity ($\underline{C}_Q$). $\underline{C}_Q$ is still a significant factor in the selection of comprehensive pipeline condition assessment techniques, such as the Impact Echo technology; however, as can be observed from Table 5, many state-of-the-art ALDTs are currently incapable of accurately determining severity information. Consequently, among the four criteria considered in this study, cost, access requirements, and reliability are given specific preferences compared to the ability to quantify severity. As can be observed from Figures 3-6, each of the 27 "what-if" cases are defined by the mean percentage weightings assigned to cost, reliability and access requirements criteria. The percentage criteria preferences are simulated using Monte-Carlo method, and in each simulation, optimal ALDT is determined using the traditional MCDA method (Yaraghi et al., 2015). For example, the mean percentage weighting for the cost criterion varies from 90% in case 1 (which represents an application scenario with significant importance given to cost criterion) to 30% in case 27 (which represents an application scenario with less importance given to cost criterion). The actual weightings of these criteria are randomly generated in a ±5% range of the defined mean weightings (i.e., in range of 25-35% for cost in case # 27 and 85-95% in case #1). Accordingly, the percentage weighting of C_Q is determined such that the sum of the weightings of four criteria adds up to 100% in each "what-if" case. The R-squared values of all pairs of criteria over different scenarios were found to be less than 0.001, which signifies the mutual exclusiveness of the randomly generated variables. To arrive at statistically significant results, the MCMCDA code is run for 1,000 simulations for each "what-if" case and each application scenario. The percentage of 1,000 simulations in which each ALDT is chosen as the optimal technique for each what-if case in application scenarios SC1, SC2, SC3, and SC4 are presented in Figures 3, 4, 5 and 6, respectively.

4.2 Results and Discussion

The selection preferences of ALDTs for scenario SC1 are presented in Figure 3. For each of the 27 "what-if" cases, Figure 3 shows the distribution of most preferred ALDTs as a percentage of 1,000 simulations. It can be observed from Figure 3 that LD is found to be a highly preferred technique in all the 27 what-if cases. NL/LNC are not found to be preferable for SC1. It can also be observed from Figure 3 that FSA is found to be highly preferable in few of the 1,000 simulations for cases 19, 21, and 23, where combined preference weightings of reliability and quantification of damage severity are comparable to the combined weightings of cost and pipeline access requirement. The observed trends of LD's superior preference with higher cost weighting is mainly due to its cheaper cost, as can be seen from Table 5, which is also consistent with the leak detection practice based on relevant literature (EPA, 2010; Rizzo, 2010). The general percentage selection of LD decreased by reducing the cost weighting to 0.3 in case 19 while that of FSA increased; however, by increasing the accessibility weighting in case 20, LD becomes the only preferred option as it is more convenient for use compared to FSA(EPA, 2010). Similarly in 21st and 23rd cases, increase in reliability weighting and decrease in accessibility weighting (as highlighted in Figure 3) at low cost, supported the selection of FSA, which is in good agreement with the current leak detection practice as it requires specific operator expertise to successfully use LD (EPA, 2010; Hamilton and Charalambous, 2015). While the trends presented in Figure 3 are generic in nature, it should be noted that NL is usually more preferred than LD for applications in noisy urban areas, e.g., high traffic zones, for it can pick up leak-induced sounds that are neither audible to the human ear nor to typical listening rods employed in LD (Hunaidi, 2012; Li et al., 2015; El-Abbasy et al., 2016). Additionally, NL is a particularly suitable option for leak detection in low-pressure pipelines (Lander, 2005; Sánchez et al., 2005; Hamilton, 2009; Hamilton and Charalambous, 2015). LNC, on the other hand, is usually employed for pinpointing a leak in suspected regions, especially in case of pipelines that exhibit lower signal attenuation. Furthermore, the combined NL and LNC system is reportedly efficient for near real-time detection and pinpointing of leaks (Brennan et al., 2008; Hunaidi, 2012; Nestleroth et al., 2012; Hamilton and Charalambous, 2015).

As can be observed from Figure 4, FSA is found to be the only preferred technique for SC2 in as many as 22 what-if cases and most preferred in four more cases. It can also be inferred from Figure 4 that the percentage preference of LNC is considerable when reliability (≤ 0.1) and quantification of damage severity (≤ 0.1) weightings are low, while access requirement (≥ 0.3) weighting is moderate and cost (≥ 0.5) weighting is high, simultaneously, as highlighted in Figure 4. This observation is analogous to the literature revealed knowledge, as LNC is reportedly less reliable than internal ALDTs for large dimeter pipes, and is also reported to be challenged by constant non-leak noises (Hamilton and Charalambous, 2015).

It can be seen from the first 11 what-if cases in Figure 5 that LNC is found to be the only preferred technique among the three suitable ALDT candidates for SC3 when cost is the main criterion of concern. When the cost preference weighting is moderate (= 0.4), the percentage selection of TA and FSA, which have similar performance scores for all criteria, are found to be increasing, specifically when the reliability weighting is increased and access requirement weighting is decreased, i.e. states 14, 16, and 18. In majority of cases 19-27 where cost is not the highest priority, TA and FSA are found to be the preferable options. Furthermore, percentage selection of LNC significantly decreased when reliability weighting has increased and access requirement weighting has decreased, i.e. states 21, 23, and 25.

For SC2 and SC3 application scenarios, it should be noted that FSA and TA are complementary techniques with FSA being more suitable for inspecting longer pipeline lengths with each insertion, while TA is more suitable for shorter distances or in cases where large numbers of lateral connections exist (EPA, 2010). Although FSA is found to be highly preferred in several what-if cases in Figure 4, it may not be always convenient to employ FSA technique because it needs access to the inside of the pipeline which may be inconvenient to utility owners (Hamilton and Charalambous, 2015). Furthermore, employing TA and FSA may be too expensive for small diameter plastic pipes (SC3) which are currently not as concerning to water utilities as the deteriorating metallic pipelines. LNC, on the other hand, as an external ALDT may be suitable for locating leaks in SC2 and SC3 scenarios, especially when using correlation techniques with hydrophones (Hamilton and Charalambous, 2015), albeit less likely preferred mainly due to the high signal attenuation rate in these scenarios and the resulting difficulty associated with sensing leak-induced changes through external transducers. Considering the difficulties and the economic considerations associated with the application of internal ALDTs for small diameter pipelines, there is a need for a technique that is economical and suitable for this class of pipelines.

It can be observed from Figure 6 that FSA is found to be the only preferred technique among the three suitable ALDT candidates for SC4. However, as pointed out previously in this paper, FSA is more suitable for inspecting longer pipelines, while TA is more suitable for shorter lengths. It is worth noting that AE, which is a suitable ALDT for SC4, offers additional insights on the pipeline condition such as remaining wall thickness and defect depth, thereby making it more suitable for a comprehensive pipeline inspection and not just leakage surveys (Nestleroth et al., 2012).

It should be noted that the results presented in this paper are based on the ALDT scores derived from the literature after reasonable interpretations are made for meaningful comparisons where limited quantitative data is available. Consequently, the selection preferences of ALDTs, as presented in this paper, should be interpreted only as primitive because they may vary depending on the availability of more accurate data on ALDTs' performance.

Furthermore, in order to validate the performance evaluation presented in this paper, brief interviews of eight water utility professionals have been conducted. These experts represented water utilities and consulting companies. The lower expert participation reflects the fact that there are fewer experts that are knowledgeable about all the ALDTs reviewed in this paper; it should however be noted the expert inputs were largely congruent. In an attempt to minimize possible bias of one expert from unduly influencing the validation outcomes, the Delphi concept is used (Okoli and Pawlowski, 2004; Kauko and Palmroos, 2014; Tricco et al., 2016). During multiple interactions with the respondent group, the responses from preliminary interactions are summarized and recirculated to identify and redress areas of disagreements (Hsu and Sandford, 2007). The experts were asked to choose suitable candidates for the four application scenarios based on the four decision criteria using their experiential knowledge. It was understood from their responses that cost and access requirements are the typical criteria of concern in the case of small diameter pipelines (SC1 and SC3), whereas reliability is a highly concerning criteria in the case of large diameter pipelines (SC2 and SC4). Summarizing the collective responses of the interviews, it was found to be customary for SC1 application scenario to adopt a straightforward leak survey procedure in which leakage presence is detected followed by the pinpointing of leaks with the combined total cost ranging between \$125-\$250 per km. Consistent with the findings of this paper for SC1, LD as one of the oldest and straightforward ALDTs is often employed in practice for small diameter metallic pipelines where reliability may not be a great concern. It was opined by the respondents that LD might be rarely successful in crowded areas where leak-induced noises are difficult to hear by the operator and consequently NL is meritorious and becomes preferable in such scenarios. Once the leak is detected and the potential leaky area is narrowed down to a smaller region, leak locating is typically carried out using LNC technique. FSA is beneficial for SC1 scenario only if reliability is of great concern and higher costs can be justified. Similarly, expert responses were found to be consistent with the findings presented in this paper for other application scenarios as well. In an attempt to facilitate the adoption of this study’s findings into practice, they are summarized in the form of a simple algorithmic flowchart illustrated in Figure 7, after additional practical considerations such as background noise levels and inspection lengths are appropriately incorporated. The selection guidance presented in Figure 7 should be further corroborated and extended in the future as the reviewed ALDTs continue to evolve into techniques that are more sophisticated.

5. CONCLUSIONS AND RECOMMENDATIONS

Leakage of treated water in distribution system pipelines is one of the most concerning issues water utility owners currently face in the U.S. With the pipeline infrastructure deteriorating and the funding gap widening over the past few years, the technological needs for pipeline monitoring and rehabilitation have grown. Although innovative technologies are available for leak detection in water pipelines, there is limited aggregation of performance data and selection guidance available, which hinders their effective practical usage. This study attempted to address this specific gap in the body of knowledge by aggregating available performance data on ALDTs and comparatively evaluating those for developing optimal selection preferences. Given the popularity of acoustics-based leak detection techniques (ALDTs), this paper reviewed six commercial ALDTs and made recommendations for appropriate techniques for various typical application scenarios. The techniques evaluated include listening devices, noise loggers, leak noise correlators, free-swimming acoustic, tethered acoustics, and acoustic emissions. The criteria based on which these six techniques are evaluated in this study include cost, reliability, ability to quantify leakage severity, and pipeline access requirements. The performance evaluation presented in this paper is primarily based on the published literature in the form of research articles and reports summarizing several practical demonstrations. While a traditional multi-criteria decision analysis (MCDA) approach is employed for the selection of an optimal

ALDT given an application scenario, Monte-Carlo approach is used to address the uncertainty inherent to published ALDT performance data as well as the subjective interpretations made to be able to compare the performance of all ALDTs.

According to findings of this study, listening devices and leak noise correlators are found to be appropriately suitable for detecting and locating leakage of small diameter metallic pipelines. Monitoring of large diameter metallic and small diameter plastic pipelines is however reported to be problematic with conventional techniques such as listening devices and leak noise correlators, due to the greater attenuation of acoustic noises. In these cases, free-swimming acoustic and tethered acoustic techniques are found to be appropriately suitable. Additionally, free-swimming acoustic and tethered acoustic techniques are found to be suitable for detecting leakage in large diameter concrete transmission mains, as well. It should be noted that the findings of this study are consistent with the inputs from brief interviews conducted with eight water utility experts. It is worth mentioning that a few of the ALDTs evaluated in this study are expected to be improved based on on-going R&D and consequently, their suitability and performance scores need to be updated periodically. Furthermore, the results should be interpreted cautiously as the application scenarios are average representations of typical industry needs and may not hold true under unique constraints and specific requirements. The study approach can be adapted in the future to develop selection guidance for other types of defect detection technologies; for example, technologies for evaluating pipe wall condition. The limitations of this study include: (a) the use of a rather simple scale for performance evaluation of ALDTs; and (b) the lack of sufficient quantitative performance data of various ALDTs and the subsequent interpretation of the available qualitative knowledge for developing ALDT scores.

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LIST OF FIGURE CAPTIONS

Figure 1. Schematic representation of various acoustic-based leak detection methods: (a) Listening Devices; (b) Noise Loggers; (c) Leak Noise Correlators; (d) Free Swimming Acoustic; (e) Tethered Acoustic; and (f) Acoustic Emission

Figure 2. Monte-Carlo Multi-criteria Decision Analysis (MC-MCDA) algorithm used in this study

Figure 3. ALDT selection preferences for scenario SC1

Figure 4. ALDT selection preferences for scenario SC2

Figure 5. ALDT selection preferences for scenario SC3

Figure 6. ALDT selection preferences for scenario SC4

Figure 7. A guidance chart for choosing ALDTs

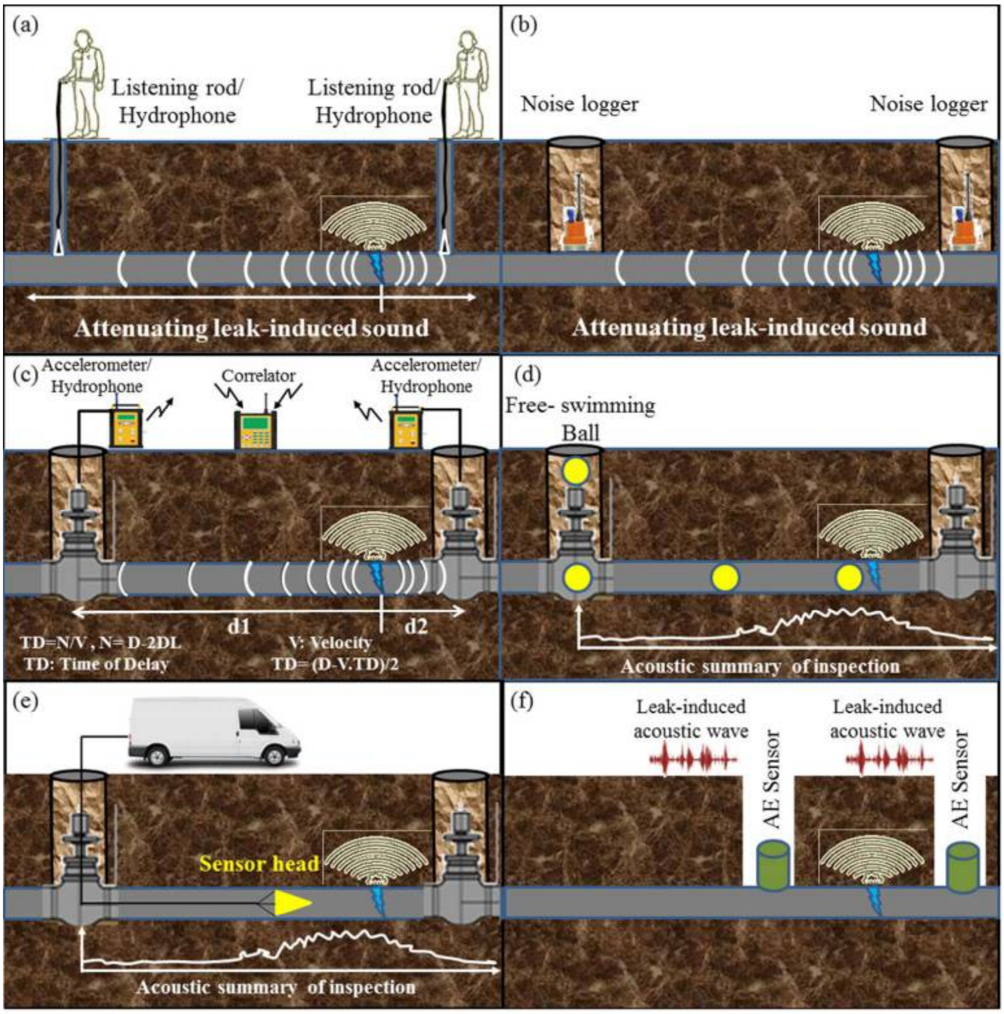


Figure 1. Schematic representation of various acoustic-based leak detection methods: (a) Listening Devices; (b) Noise Loggers; (c) Leak Noise Correlators; (d) Free Swimming Acoustic; (e) Tethered Acoustic; and (f) Acoustic Emission

272x274mm (96 x 96 DPI)

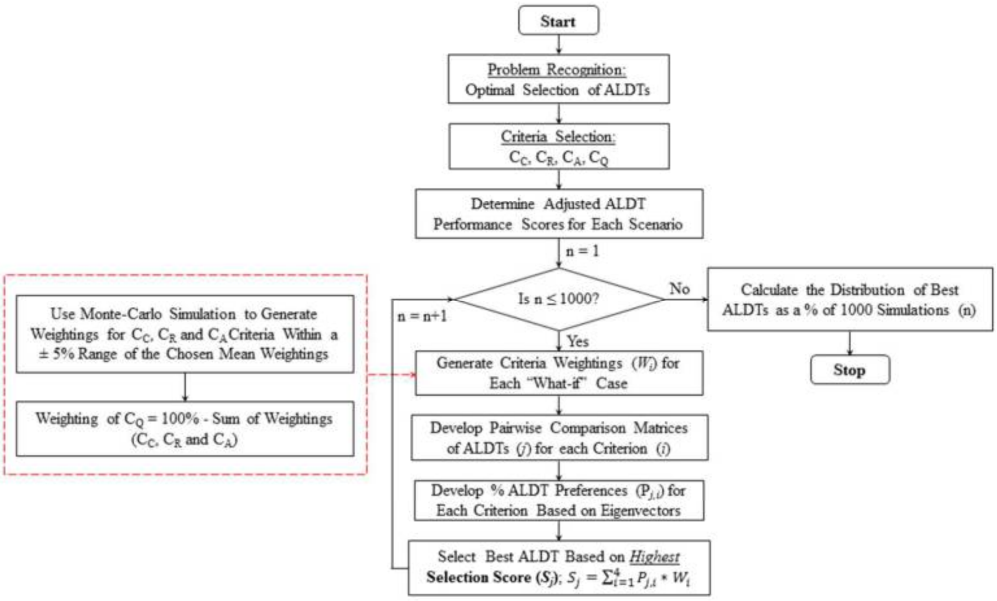
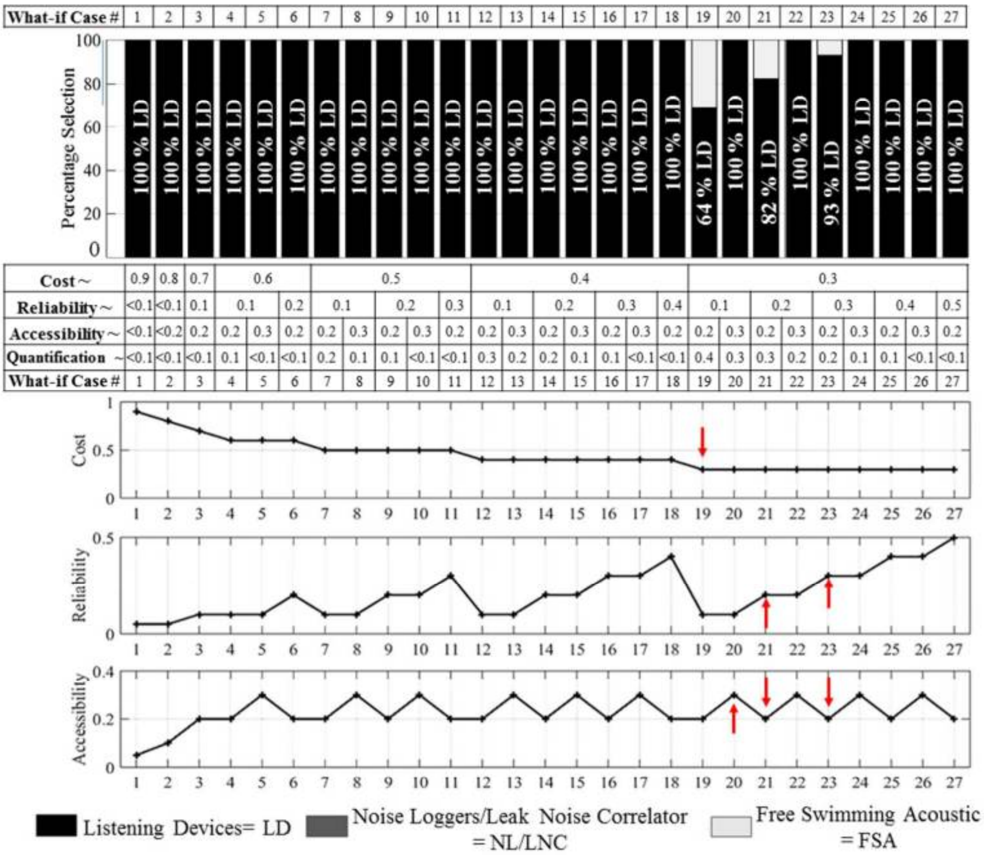


Figure 2. Monte-Carlo Multi-criteria Decision Analysis (MC-MCDA) algorithm used in this study

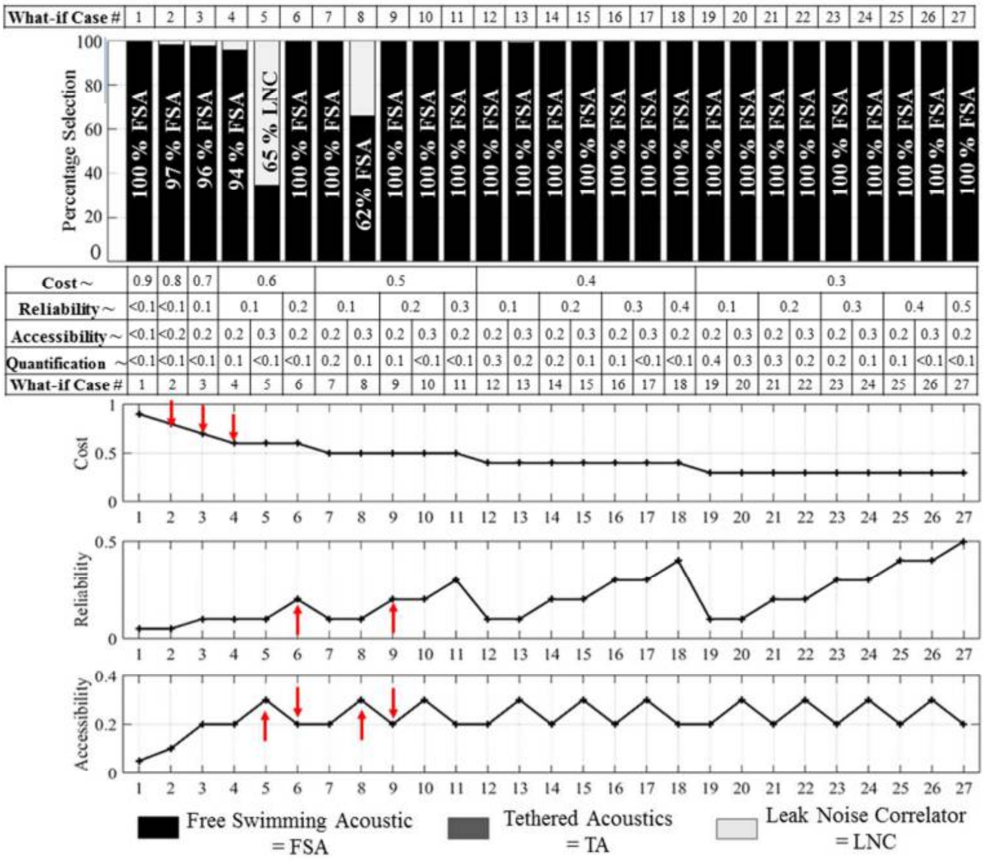
259x155mm (96 x 96 DPI)



What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Cost ~	0.9	0.8	0.7	0.6			0.5					0.4							0.3								
Reliability ~	<0.1	<0.1	0.1	0.1		0.2	0.1		0.2		0.3	0.1		0.2		0.3		0.4	0.1		0.2		0.3		0.4		0.5
Accessibility ~	<0.1	<0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
Quantification ~	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.2	0.1	0.1	<0.1	<0.1	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1	0.4	0.3	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1
What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Figure 3. ALDT selection preferences for scenario SC1

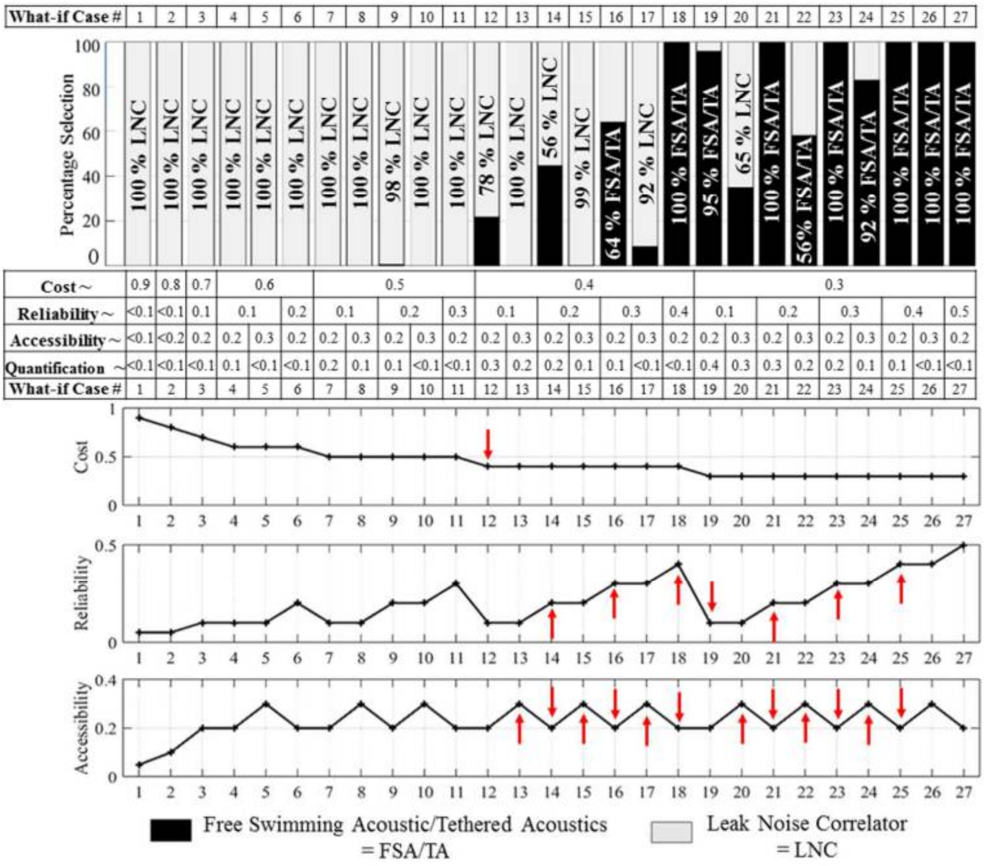
254x220mm (96 x 96 DPI)



What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Cost ~	0.9	0.8	0.7	0.6			0.5					0.4							0.3								
Reliability ~	<0.1	<0.1	0.1	0.1		0.2	0.1		0.2		0.3	0.1		0.2		0.3		0.4	0.1		0.2		0.3		0.4		0.5
Accessibility ~	<0.1	<0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
Quantification ~	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.2	0.1	0.1	<0.1	<0.1	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1	0.4	0.3	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1
What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Figure 4. ALDT selection preferences for scenario SC2

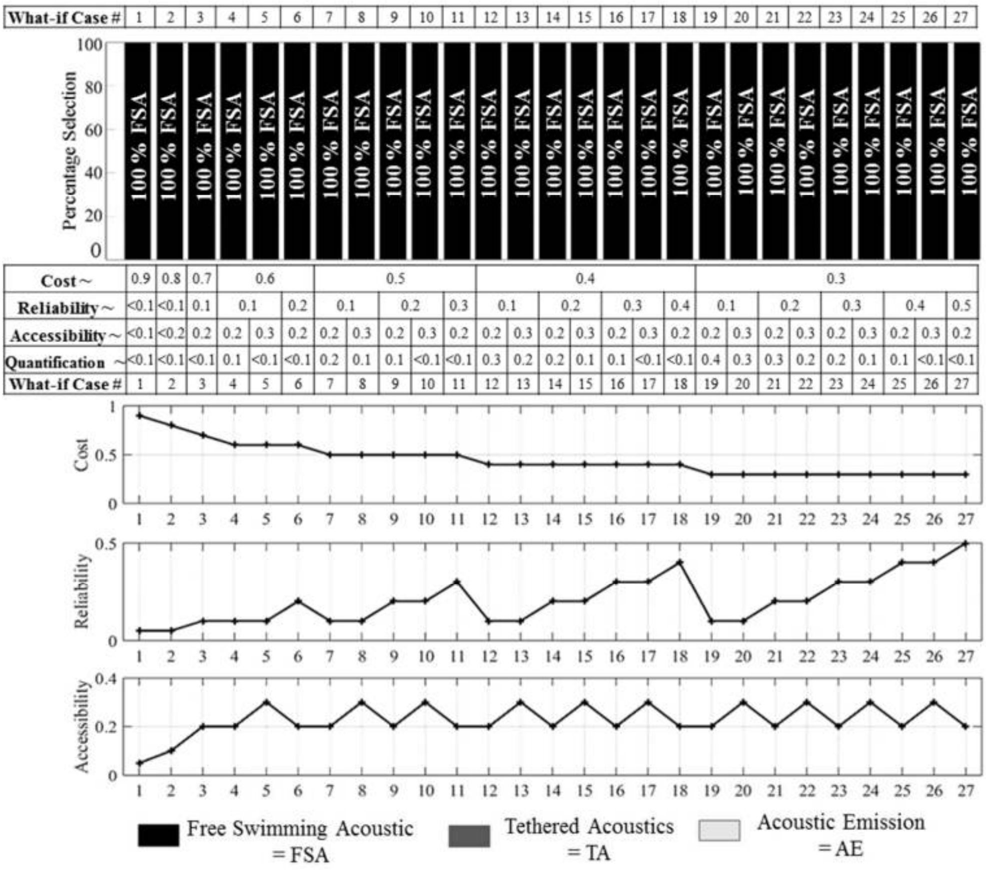
251x219mm (96 x 96 DPI)



What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Cost ~	0.9	0.8	0.7	0.6			0.5					0.4							0.3								
Reliability ~	<0.1	<0.1	0.1	0.1		0.2	0.1		0.2		0.3	0.1		0.2		0.3		0.4	0.1		0.2		0.3		0.4		0.5
Accessibility ~	<0.1	<0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
Quantification ~	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.2	0.1	0.1	<0.1	<0.1	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1	0.4	0.3	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1
What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Figure 5. ALDT selection preferences for scenario SC3

251x218mm (96 x 96 DPI)



What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Cost~	0.9	0.8	0.7	0.6			0.5					0.4							0.3								
Reliability~	<0.1	<0.1	0.1	0.1		0.2	0.1		0.2		0.3	0.1		0.2		0.3		0.4	0.1		0.2		0.3		0.4		0.5
Accessibility~	<0.1	<0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
Quantification ~	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.2	0.1	0.1	<0.1	<0.1	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1	0.4	0.3	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1
What-if Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Figure 6. ALDT selection preferences for scenario SC4

251x219mm (96 x 96 DPI)

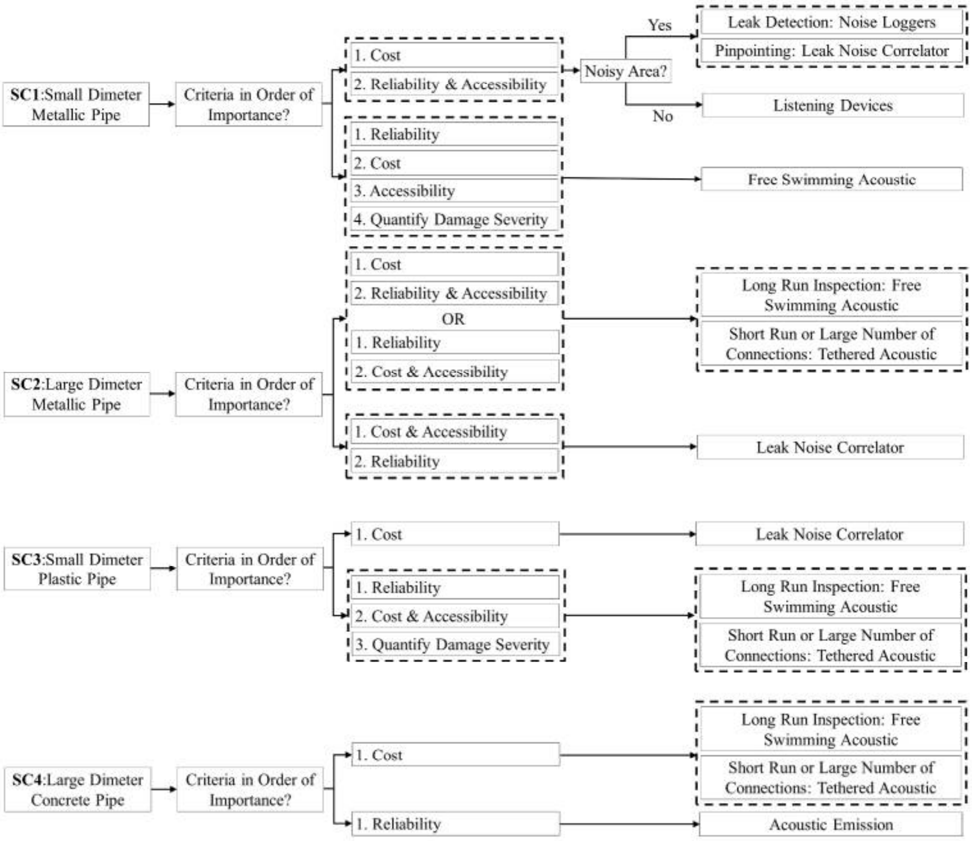


Figure 7. A guidance chart for choosing ALDTs

762x660mm (96 x 96 DPI)

Table 1. Classification of water pipeline inspection techniques

Non-acoustic	Direct	- Visual inspection: Closed-circuit television (CCTV) inspection, Laser Scan (LS) - Electromagnetic methods: Magnetic flux leakage (MFL), remote field eddy current (RFEC), broadband electromagnetic (BEM), pulsed eddy current (PEC) testing, ground penetrating radar (GPR), ultra-wideband (UWB) pulsed radar system - Ultrasound methods: Guided wave ultrasound (GWU), Discrete Ultrasonic Measurement (DUM), Phased array technology (PA) - Radiographic methods (RM): Gamma or X-ray - Thermography (TM) - Fiber-optic sensors (FOS)
	Indirect	- Soil characterization analysis (SCA): Such as moisture content of the soil, PH value and soil resistivity - Hydraulic-based methods (HBM): Inverse transient analysis, Free vibration analysis, Time domain reflectometry techniques, Pressure analysis, computational pipeline monitoring (real-time transient model), Volume balance
Acoustic	Leak detection only	Listening devices, leak noise correlator, noise loggers
	Leak detection and structural condition inspection	Free swimming, tethered, acoustic emission

Table 2. Advantages and limitations of various acoustic-based leak detection techniques

Technique	**Advantages**	**Limitations**
Listening Devices	- Suitable for asbestos cement and metallic pipes (diameter < 300 mm) - Relatively inexpensive - Minimal system interruption - Needs no further analysis	-Not suitable for non-metallic pipes (except asbestos cement) or large diameter pipelines unless the devices are placed in a close proximity of the leak's location (Hunaidi, 2012) -Not suitable for locating leaks or quantifying their severities -The technique is operator skill-dependent and extensive training is required
Noise Loggers	- Minimal system interruption - Suitable for low-pressure pipelines - Low cost battery and maintenance expenses	-Not suitable for locating leaks or quantifying their severities -High rates of false alarms and its hardware reliability is also questionable (Van der Kleij and Stephenson, 2002; Hunaidi, 2012) -Ad-hoc/temporary survey using NL is not cost effective as it is estimated to be three times more expensive than LD (Pilcher, 2003; Hunaidi et al., 2004; Hamilton, 2009; Hunaidi, 2012)
Leak Noise Correlator	- Minimal system interruption - A beneficial option for leak locating in small diameter metallic pipelines	- Inefficient and expensive for plastic and large diameter metallic pipes - Higher chances of missing small leaks due to the possible masking of their signals by ambient noises and large leaks due to the presence of softeners[1] (Hunaidi, 2012) - Extensive operator training is required - Not suitable for quantifying leak severity (Nestleroth et al., 2012)
Free Swimming Acoustic	- Minimal system interruption - Pushes the practical limits of inspecting long pipeline sections with a single launch	- Relatively expensive - Not suitable for complex pipeline configurations - Not suitable for high pressure systems (>400 psi) - There is a chance of losing the ball during inspection when unknown conditions are encountered.
Tethered Acoustics	- Minimal system interruption - Suitable for any pipe material - Suitable for shorter inspection length or mains with more lateral connections (Nestleroth et al., 2012)	- It can be expensive - FSA and TA are both comparable in terms of equipment cost; however, TA inspection tends to be more expensive as its hardware needs to be housed in a large vehicle during inspection.
Acoustic Emission	- Low maintenance requirements	- Developing standards to easily calibrate the equipment and preparing a library of acoustic signatures of known events still remain incomplete - Service might be interrupted during the installation of sensors, which may lead to customer dissatisfaction - Not capable of quantifying leakage severity (Anastasopoulos et al., 2009) - Higher chances of false alarms (Xu et al., 2012)

1) A chemical additive used to reduce mineral content of the water

Table 3. Application scenarios for ALDTs

Scenarios	Description	Suitable ALDTs
SC1	Metallic; <300 mm dia.	LD, NL, LNC, FSA TA(1), ∀ 250mm ≤ diameter < 300mm
SC2	Metallic; ≥300 mm dia.	FSA, TA, LNC
SC3	Plastic; <300 mm dia.	TA(2), FSA(2), LNC
SC4	Concrete; >600 mm dia.	TA, FSA, AE

(1) TA is suitable for SC1 but not commonly used for financial reasons

(2) Employing TA or FSA may be too expensive for small diameter plastic pipes which are currently not highly concerning to many water utilities

Table 4. Criteria scoring for evaluating ALDTs

Criterion	Rating Type	Evaluation Ratings		
		Scores [1= least preferred; 3 = highest preferred]		
C_R	Qualitative	Low	Moderate	High
	Quantitative	1	2	3
C_Q	Qualitative	Incapable	Somewhat capable	Capable
	Quantitative	1	2	3
C_A	Qualitative	Pipeline surface	Insertion and extraction only	Above ground
	Quantitative	1	2	3
C_C	Qualitative	High	Moderate	Low
	Quantitative	1	2	3

Table 5. Evaluation of ALDT candidates for the four application scenarios

Criteria	SC1				SC2			SC3			SC4		
	LD	NL	LNC	FSA	FSA	TA	LNC	FSA	TA	LNC	FSA	TA	AE
Cost (C_C[1])	3	2	2	1	2	1	2	1	1	2	2	1	1
Reliability (C_R)	2	2	2	3	3	3	1	3	3	1	3	3	2
Quantification of Severity (C_Q)	1	1	1	2	2	2	1	2	2	1	2	2	1
Access Requirement (C_A)	3	3	3	2	2	2	3	2	2	3	2	2	1

(1)NL for temporary mode requires patroller unit for transmitting data with unit cost of $8,000/each and Permalog loggers for data collection which costs about $450/each (Stringer et al., 2007). The unit cost excluding preparation cost, traffic control and other logistical support is reported to be $16/m for FSA on average, while it is $7/m for longer inspections and $13/m for shorter runs in the case of TA (Nestleroth et al., 2012). The unit cost of the LNC technique with improved correlation function is reported to be $7/m (excluding costs of preparation, traffic control and logistical support) (Nestleroth et al., 2012). Furthermore, the preparation cost of the enhanced LNC is less than FSA and TA (Nestleroth et al., 2012).