Application of acoustic intelligent leak detection in an urban water supply pipe network

Zhang Xue, Lin Tao, Jiang Fuchun, Edmund Riehle, Hu Xiang, Ni Bowen and Rajendra Prasad Singh

ABSTRACT

Different leakage detection technologies present different efficiency and precision of leakage detection in water distribution systems due to their own properties. This study aimed to investigate the use of acoustic sensors to locate the exact position of leaks, which work 24 hours per day in different modes, i.e. fixed installation and mobile exploration. The results showed that the maximum distance between the acoustic sensors installed on the pipeline was 380 m. Field application results indicated that detecting threshold of the distance was 300 m and the intensity ratio of leaking state noise (LSN) to background noise was 1.9 respectively. The pipeline length by manual hunting area (MHA) is 1.3 times longer than the acoustic logger tested area (ALTA), but the detected leakage points in MHA is 20% less than in ALTA. Furthermore, the cost of leakage detection in MHA was about 6,000 yuan/detected leakage point. That in ALTA was about 2,500 yuan/detected leakage point. The case study also indicates that the acoustic logger is a promising tool with the advantage of lower cost and faster detection, compared to manual ground listening with a sound stick. The acoustic leakage detection method can detect the leakage in different sized pipelines, whereas the manual detection was concentrated in small-sized pipelines.

Key words | acoustic detection, correlator, leak detection, water distribution system

Zhang Xue
Lin Tao (corresponding author)
Department of Municipal Engineering,
Hohai University,
Nanjing 210098,
China
E-mail: *63197458@qq.com*

Zhang Xue
Jiang Fuchun
Hu Xiang
Ni Bowen
Suzhou Water Supply Company,
Suzhou 215002,
China

Edmund Riehle
F.A.S.T. GmbH,
Stuttgart,
Germany

Rajendra Prasad Singh
School of Civil Engineering,
Southeast University,
Nanjing 210096,
China

HIGHLIGHTS

- Acoustic sensors were investigated to assess the characteristics of identification and detection accuracy.
- Recommended intervals of two sensors was less than 300 m.
- Precise threshold values between background and leaking noise were obtained, as it is important to check initial and pre-existent leaks.
- Economic benefit (EB), detection efficiency (DE) and detection speed (DS) of acoustic detectors were better than manual listening method.
- Leakage detection by manual methods becomes more difficult with the increase in depth.

INTRODUCTION

Urban water supply and distribution systems are important infrastructures of any city. It has been reported that the percentage of water leakage from distribution systems was even higher than 50% in some cities around the world, such as Jakarta, Delhi, Adana, etc. (McIntosh 2003; Sheng & Jinghui 2014; Porwall *et al.* 2018; Boztaş *et al.* 2019). According to the '2016 Statistical Yearbook of Urban Construction' of the Ministry of Housing & Urban-Rural Development of the People's Republic of China (2017), the maximum percentage of leakage in some Chinese cities were as high as 78%.

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Many Chinese cities have underestimated the leakage of water distribution systems. Therefore, it is still difficult for water companies to control leakage.

The nonrevenue water (NRW) attributed to pipeline leaks, which is known as physical leakage, is estimated as 30% of the total flow (Jinghui *et al.* 2019). Water loss in the distribution system is more than 80%, compared to the water mains (Jinghui *et al.* 2019). Physical leakage prevention has become a mandatory research agenda of integrated water management systems. Generally, leakage detection methods of the system were classified into two different categories, namely regional leakage identification and pinpoint location. The online hydraulic model is used for leakage detection and district metering area (DMA) is applied for leakage control (Guo *et al.* 2013; Mamadea *et al.* 2014; Wu *et al.* 2016). Due to the limitations of the quantity of pressure meters and the ability to find small pressure differences, the detection precision identified with the online hydraulic model is not very applicable. The DMA method usually uses clustering algorithms to analyze minimum night flow (MNF) that read from the flow meters to determine the abnormal flow. The effectiveness depends on the scale, hierarchy of partitions and accuracy of flow meters (Aumanand & Konnur 1996; Gao *et al.* 2005a, 2005b; Hunaidi *et al.* 2005; Giustolisi *et al.* 2008; Loureiro *et al.* 2014; Chen *et al.* 2018. Assuming that there is approximately 5% of flow error among the flow meters, there could be an error of 100 m^3/h for a district with a water consumption of 2,000 m^3/h. This kind of leakage-control program is often used to survey leakage of an area, which can be quickly identified by the pressure and flux meters (Zheng & Kleiner 2012; Li *et al.* 2014; Sadeghioon *et al.* 2014; Tao *et al.* 2016; Yu 2017). A pinpoint location method can further narrow the leakage position from a small area which was identified by the regional method. Generally, two types of listening methods are used in leakage detection systems, namely active and passive detection methods. Manual ground listening with a sound stick has been widely used for a long time with relatively high accuracy. However, this method has large weaknesses due to the attenuation of sound in the soil, pavement medium and other factors, as well as worker fatigue. Therefore, manual listening is mostly used as a passive leakage finding method when there is some evidence of possible leakage. In contrast, active leakage detection and control is gaining in popularity among water companies.

Currently, useful and feasible technology-based approaches such as easy installation, low cost, less power consumption and non-destructibility methods are needed to monitor and detect the running pipeline. Many researchers proposed acoustic sensors to locate the leakage in water storage and distribution systems. Techniques based on the monitoring of leak-related noise and vibrations are by far the most commonly adopted (Hunaidi *et al.* 2000; Gao *et al.* 2005a, 2005b; Martini *et al.* 2017, 2018; Yazdekhasti *et al.* 2018). The hydrophone sensors installed inside the pipeline and acoustic loggers placed on the valves or hydrants along the pipeline have been increasingly used to locate leakages (Muggleton & Brennan 2003; Gongtian *et al.* 2013; Michael *et al.* 2014; Alicja & Andrzej 2016; Fatih *et al.* 2017; Haibat & Jae-ho 2019). Detecting the range and accuracy of hydrophone sensors is better than acoustic loggers, but pipelines can be easily damaged due to the installation of hydrophone sensors. Applying an acoustic logger does not need drilling of pipelines. It is a low-cost, compact-size and non-destructible sensor (Gongtian *et al.* 2013; Haibat & Jae-ho 2019). Furthermore, these techniques are non-invasive and can be applied without altering the operational conditions of the network (Martini *et al.* 2017). An acoustic logger based on measuring noise signal may not achieve satisfactory results because of the interference of background noise (Martini *et al.* 2017, 2018). The correct threshold values characterizing the background noise associated with the non-leaking state is essential for their effectiveness (Martini *et al.* 2017, 2018; Bach *et al.* 2020). Measurements of the ratio between background and leaking noise is important to check initial and pre-existent leaks (Martini *et al.* 2017, 2018; Bach *et al.* 2020). The Enhance Constant Faults Alarm Rate (ECFAR) algorithm has been proposed for isolating the burst waveform (Bach *et al.* 2020). Due to the difficulty of detection, the strategy with multiple detection techniques has been applied to investigate a complex underground water distribution system in one community in China (Shifan *et al.* 2020). The absence of reliable data and mature computation methods has restricted the large application of acoustic loggers in China. Some experimental campaigns have been conducted to assess the effectiveness of leak detection and locating. However, few records can be found to verify the success of these methods in practice.

In this paper, we tested the performance of acoustic sensors to accurately locate leakages in different modes of fixed installation, mobile exploration or in a combined way. In particular, characteristics of the identification and detection accuracy were tested in different frequency and installation distances. In addition, acoustic signals related to the active leaks and the non-leaking condition were measured to identify the relation between the intensity ratio of leaking state noise (LSN) to background noise and the detection precision. Finally, two detection datasets are used to compare the detection performance of acoustic detectors and the manual listening method in the field experiment.

MATERIAL AND METHODS

Characteristics of acoustic logger

A schematic diagram of acoustic detectors is presented in Figure 1. The system consists of a pipeline monitoring sensor, on-site inspection platform and online monitoring operation platform. There are two types of classical work mode for acoustic detectors. When leakage noise is detected by the acoustic logger, it can be received by repeaters and sent to servers for analysis. The noise read by the logger can also be transmitted to the on-site inspection platform for remote monitoring by the inspector. In the experiment, every signal from acoustic loggers was received by the on-site inspection platform for field staff.

Trial experiments were conducted at Suzhou Water Supply Company (SZWSC) in Suzhou, China. The experiments consist of two parts: a practical experiment in Xiang Cheng waterworks and a field experiment in the residential economic zone. The experiment design is shown in Figures 2 and 3.

Pilot experiment

A schematic diagram of the acoustic detection test is presented in Figure 2. The experiments were conducted at Xiang Cheng Waterworks, Suzhou, China. The diameter and material of tested pipes is 300 mm and ductile iron respectively. Overburden depth of the pipes is about 50 cm. The pressure of the measured pipe was kept at approximately 0.30 MPa. All the acoustic sensors were installed on the pipes with valve chambers from Number Z1 to number Z8 in order to test the sensing range of the acoustic loggers. A simulated leakage in the pipe was at the point marked '0 m'. A simulated leak flow rate was controlled by the tap buried underground. All the simulated leakages of the above tests were set to 5 m^3/h. The intensity

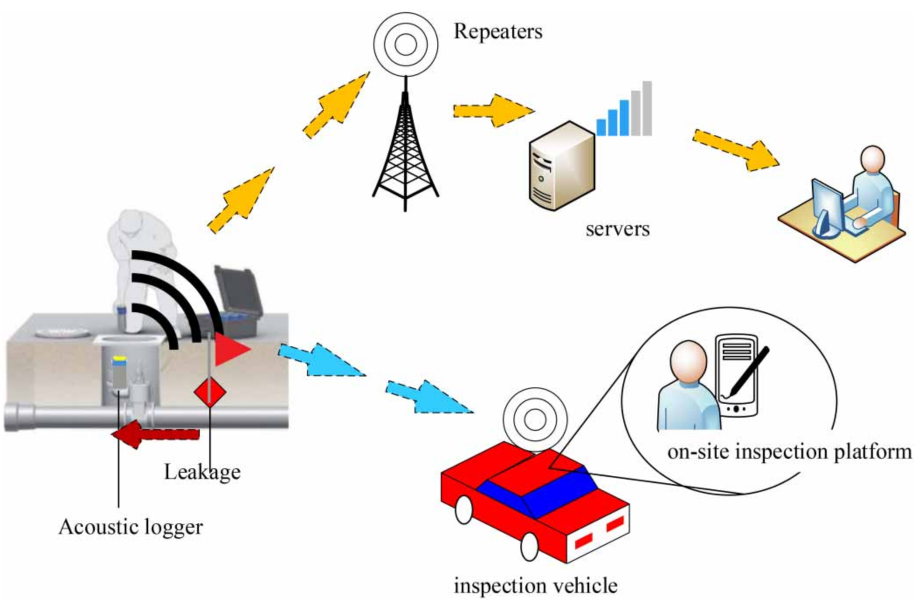

Figure 1 | Schematic diagram of acoustic detectors.

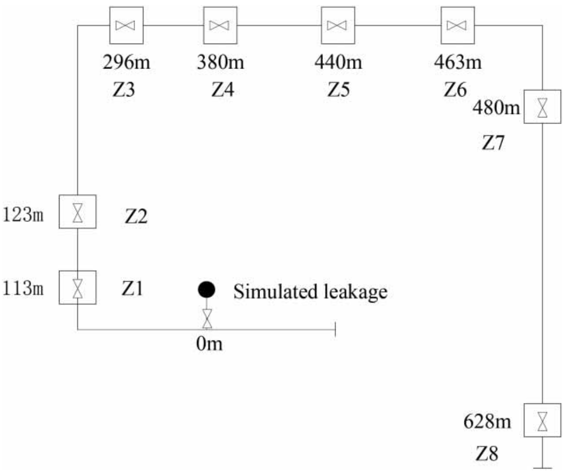

Figure 2 | Practical experiment of leakage detection with acoustic loggers at Xiang Cheng Waterworks.

of background noise was tested when the simulating taps were closing. At the opening status of the tap, sounds of simulated leakages were captured by every acoustic logger. Measurements were performed for both the non-leakage and the leakage conditions to monitor the noise of the environmental and active leaks, respectively. Using Alberto's methods (Martini *et al.* 2017, 2018), the following procedure was applied:

- Every 30 s an acquisition was started and recorded, collecting a total of six measurements in a certain condition as a data set.
- Six measurements in every point were carried out with acoustic loggers after tap closing (one acquisition every 30 s), which was regarded as non-leakage state or background noise. Average values of every data set were calculated to evaluate the background noise of every different point.
- Six measurements from every point were recorded after the tap was in the opening status. These points were regarded as a leaking state (one acquisition every 30 s). Average values of every measurement were calculated to evaluate the leaking state noise at different points.

Field experiment

A comparison test between acoustic loggers and manual detection is presented in Figure 3. The reddish part in Figure 3 is the acoustic loggers tested area (ALTA), where leakages of pipeline were detected by loggers. Acoustic loggers were installed on the pipes in the valve chamber of ALTA. Leakages of the pipeline shown in the blue part in Figure 3 were traced manually, which is called the manual hunting area (MHA).

The technical parameters of the experimental field location are shown in Table 1, in which the water distribution systems were constructed in January 2000. The diameter of pipeline in this district was 40–400 mm, of which pressure was kept roughly at 0.30 MPa. The overburden depth of the pipes was 20–100 cm. The material of small-bore pipelines with diameters less than 100 m was steel-plastic compound pipe (SPCP) and the others are ductile iron. The residential area and pipeline length of MHA were slightly larger and longer than ALTA.

Different parameters were applied to evaluate test performance, which is classified as follows:

- Economical benefit (EB): cost of leakage detection (CLD) divided by the detected leakage number (DLN), generally written in vector form:

$$\mathrm{EB} = \frac{CLD}{DLN} \tag{1}$$

- Detection efficiency (DE): detected leakage number (DLN) divided by pipeline length (PL), generally written in vector form:

$$\mathrm{DE} = \frac{DLN}{PL} \tag{2}$$

- Detection speed (DS): the detected leakage number (DLN) divided by detection time (DT), generally written in vector form:

$$\mathrm{DS} = \frac{DLN}{DT} \tag{3}$$

RESULTS AND DISCUSSION

Detection range of acoustic loggers

The results of the fixed sensors from the pilot experiment are presented in Figure 4. Comparative analysis of the noise

Figure 3 | Experiment detected with acoustic loggers and manually in the living area. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/aqua.2020.022.

Table 1 | Properties of the experimental district

			Pipeline length (PL) (m)						
	Area (m^2)	**Completion date**	**DN400**	**DN300**	**DN200**	**DN150**	**DN100**	**< DN100**	**Length**
MHA	48,475	January 2000	0	591	660	100	718	890	2,960
ALTA	66,086		56	377	275	295	597	671	2,272

intensity before and after leakage showed that the results indicated an attenuation trend with the distance increase from the leakage point. The noise intensity captured by sensors Z4 from the simulating tap was 10% higher than the background noise, but the noise intensity by sensors Z5, Z6, Z7 and Z8 were similar to background noise. Therefore, the noise made by leakage can be captured by the acoustic logger set at 380 m away from simulated leakage (i.e. sensors Z4). The acoustic detectors should be installed on the pipes at intervals of less than 380 m apart. Depending on the calculations, the 0.6 dB/m transmission loss confirmed in a previous study (Jinghui *et al.* 2019) is similar to the acoustic logger's detected value. The experimental pipe fixed on the bracket in Jinghui *et al.* (2019) study was different to the tube buried underground in this paper. In this work, the noise attenuation due to pipe leakage and solids together reduced by about 83% in 380 m and was different to previous research where the result was 90% was in 50 m (Gongtian *et al.* 2013).

Sensitivity of acoustic loggers

The alarm status of the sensor in different positions from the pilot experiment is shown in Figure 5. The red signal

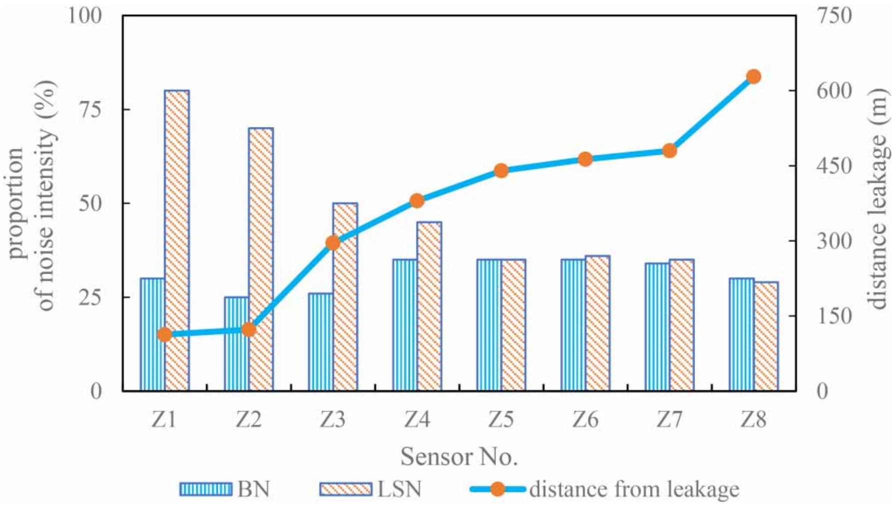

Figure 4 | Acoustic detection performance using a multi-sensor in high sensitivity mode.

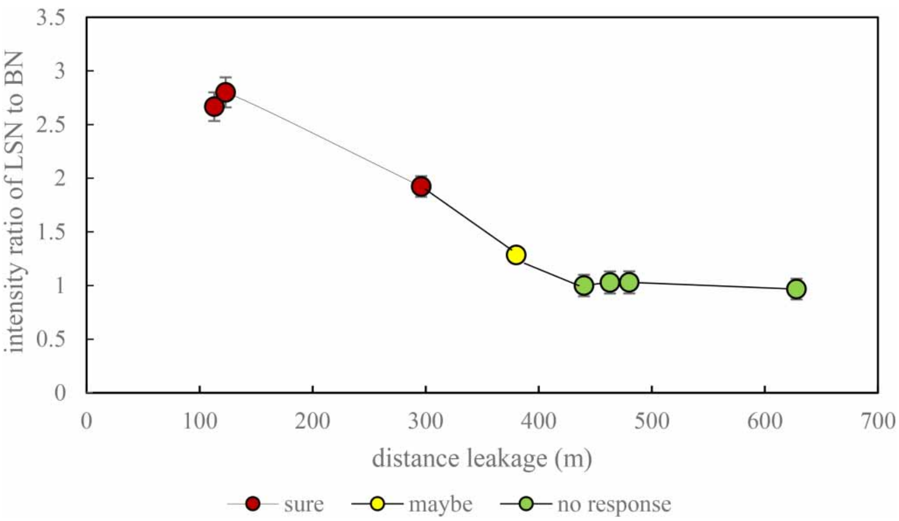

Figure 5 | Alarm status of sensors in different positions in high sensitivity mode. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/aqua.2020.022.

read from acoustic loggers represents a real leak near this sensor. The yellow and green colors illustrate the suspected signal and no signal status respectively. Based on site testing, less than 300 m from the leakage, loggers could send alerts and the intensity ratio of leaking state noise (LSN) to background noise (BN) was from 1.9 to 2.8. The logger in the valve chamber 380 m away from the leakage emitted a suspected signal, of which the intensity ratio of LSN to BN was 1.3. With the distance of 440–628 m away from the simulated leaking point, a green signal was shown on loggers, which presented the intensity ratio of LSN to BN of about 1. These results indicated that the distance of precise alarm was probably 300 m and the intensity ratio threshold was 1.9, respectively. The intensity ratio is similar to previous research at 1.82–1.86 (Miller *et al.* 1999). Previous study results reveal that 37–39 dB transients occurring at about 15 signals per second from leakage could be traced by acoustic sensors (Miller *et al.* 1999). The Acoustic Emission (AE) amplitude of our experimental environment in Xiang

Cheng water treatment plant was 45 dB. Results from the current study also resembled the location of the leakages based on Average Signal Level (ASL) values in a previous study (Didem & James 2012). Moreover, in order to obtain more precise location information on leaking points, the distance for logger installation should not exceed 300 m, and the intensity of surrounding noise should not be too high.

Practical applications performance

The test results in practical applications are shown in Table 2. The pipeline length in MHA was 1.3 times longer than ALTA, but DLN in MHA was 20% lower than ALTA. Furthermore, CLD in MHA is 48,000 Chinese yuan (RMB), converted into about 6,000 yuan per unit. The expenditure of the acoustic loggers is less than the manual detection method. With the consideration of reusing acoustic loggers, the cost of leakage detection would be even lower. With the consideration of different pipeline lengths in MHA and ALTA, the detected leakage number (DLN) of the manual method was 2.7 units per kilometer, which is lower than the acoustic loggers. The DS of the manual method is worse than acoustic loggers. Therefore, acoustic loggers have an advantage in economic and speed performance compared to manual loggers. Researchers had detected 40 leakages in Xiamen University, which saved more than 2 million Chinese yuan in two years (Jiu *et al.* 2018). The results from the study at Xiamen University are similar to the current study.

Table 2 | Test results in practical applications

Category	MHA	ALTA
DLN (units)	8	10
CLD (Chinese Yuan)	48,000	25,000
DT (days)	7	7
EB (yuan per unit)	6,000	2,500
DE (units per kilometer)	2.70	4.40
DS (units per day)	1.14	1.43

Leakage distribution with different methods

The test results detected by two methods in real application are shown in Figure 6. The leakage detected using manual methods was mainly concentrated in small-sized pipes with a diameter less than DN150, especially those less than DN100. By contrast, leakages in various pipelines with different diameters could be detected by applying acoustic loggers. For manual detection, the signal caused by pipe leakage is captured from soil above the pipe, which reduces the sound intensity. For acoustic logger's detection, the signal from leakage is transmitted by the pipe itself, which can be detected with negligible loss by the acoustic loggers fixed in the valve chamber. With the increase of pipe diameter, the buried depth of pipes increases gradually in soil. Therefore, leakage detection by

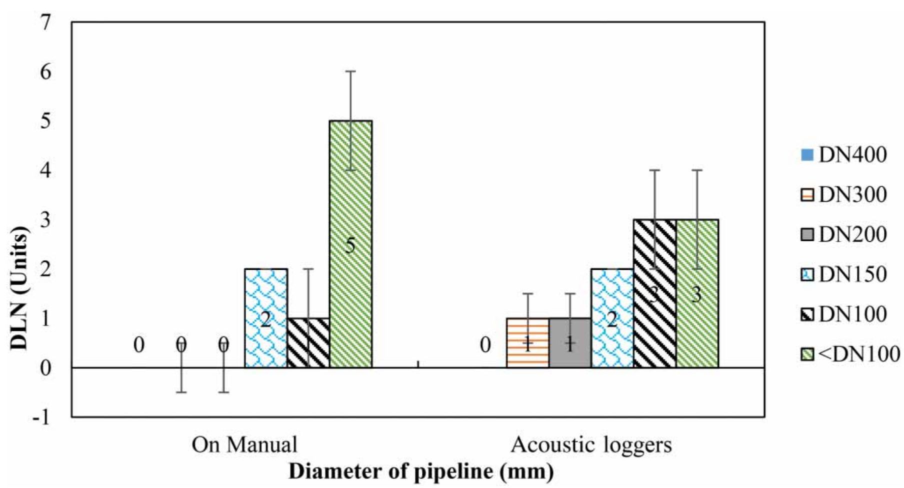

Figure 6 | Statistic of leakages detected by two methods.

the manual methods becomes more difficult as the depth increases, this is why leakage detected by manual detection is mainly concentrated in small-sized pipes.

CONCLUSIONS

Leakage detection in a water distribution system is a comprehensive task that involves many technologies. Acoustic detection devices have the advantage of locating the exact position of leakage. Compared to the manual listening method, acoustic detecting devices have no fatigue like workers. It can be operated 24 hours per day in different modes of fixed installation, mobile exploration or in a combined way. According to the sensitivity of the acoustic logger, we determined that the maximum distance between the fixed loggers is 380 m. Moreover, it is necessary for the water company to construct an integrated water management system that is composed of district metering, model detection, online acoustic detection, repair order distribution, and hotline data. By sharing these data to central management systems, leakage management can be enforced.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Alicja, B. & Andrzej, U. 2016 Monitoring system as a tool for risk evaluation in water distribution systems. In: *17th International Carpathian Control Conference (ICCC)*. IEEE Tatranska Lomnica, pp. 21–24.

Aumanand, M. A. & Konnur, M. S. 1996 A novel method of using a control valve for measurement and control of flow. *IEEE Trans. Instrum. Meas.* **48**, 813–816.

Bach, P. D., Jae, Y. K., Inkyu, J., Cheol, H. K. & Jong, M. K. 2020 Acoustic emission burst extraction for multi-level leakage detection in a pipeline. *Appl. Sci.* **1933** (10), 1–11.

Boztaş, F., Özdemir, Ö., Durmuşçelebi, F. M. & Firat, M. 2019 Analyzing the effect of the unreported leakages in service connections of water distribution networks on non-revenue water. *Int. J. Environ. Sci. Technol.* **16**, 4393–4406.

Chen, G. Y., Liu, Y. F. & Chen, Z. J. 2018 Establishment and application of the district measurement system of Shaoxing Water Department. *Water Wastewater Eng.* **54**, 125–128.

Didem, O. & James, H. 2012 Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity. *Int. J. Pressure Vessels Piping* **92**, 63–69.

Fatih, K., Ahmet, Z., Resul, K. & Sultan, Z. 2017 Leakage detection and localization on water transportation pipelines: a multi-label classification approach. *Neural Comput. Appl.* **28**, 2905–2914.

Gao, Y., Brennan, M. J. & Joseph, P. F. 2005a A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes. *J. Sound Vib.* **292**, 552–570.

Gao, Y., Brennan, M. J., Joseph, P. F., Muggleton, J. M. & Hunaidi, O. 2005b On the selection of acoustic/vibration sensors for leak detection in plastic water pipes. *J. Sound Vib.* **283**, 927–941.

Giustolisi, O., Savic, D. & Kapelan, Z. 2008 Pressure-driven demand and leakage simulation for water distribution networks. *J. Hydraul. Eng.* **134**, 626–635.

Gongtian, S., Shifeng, L. & Zhenlong, H. 2013 Development of a pipeline leakage location instrument based on acoustic waves. In *Proceedings of the World Conference on Acoustic Emission*. Springer Science & Business Media, New York, pp. 47–54.

Guo, S., Zhang, T., Shao, W., David, Z. & Yuan, Y. 2013 Two-dimensional pipe leakage through a line crack in water distribution systems. *J. Zhejiang Uni. Sci. A Appl. Phys. Eng.* **14**, 371–376.

Haibat, A. & Jae-ho, C. 2019 A review of underground pipeline leakage and sinkhole monitoring methods based on wireless sensor networking. *Sustainability* **11** (15), 1–24.

Hunaidi, O., Chu, W., Wang, A. & Guan, W. 2000 Detecting leaks in plastic pipes. *J. Am. Water Works Assoc.* **92**, 82–94.

Hunaidi, O., Wang, A., Bracken, M., Gambino, T. & Fricke, C. 2005 Detecting leaks in water-distribution pipes. *Arab. Water World* **29**, 52–55.

Jinghui, X., Kevin Tshun-Chuan, C., Guoqiang, W., Beibei, H., Eva Leong-Ching, W., Wei, L., Jason, Y., Nijhof, E. & Yuandong, G. 2019 Low-cost, tiny-sized mems hydrophone sensor for water pipeline leak detection. *IEEE Trans. Ind. Electron.* **66**, 6374–6382.

Jiu, G. L., Ya, J. S. & Guang, T. Z. 2018 Application of comprehensive water-saving models and new technologies in campus. *University Logistics Research (China)* **Supplement**, 54–56 (in Chinese).

Li, R., Huang, H., Xin, K. & Tao, T. 2014 A review of methods for burst/leakage detection and location in water distribution systems. *Water Sci. Technol. Water Supply* **15**, 429–439.

Loureiro, D., Alegre, H. & Coelho, S. T. 2014 A new approach to improve water loss control using smart metering data. *Water Sci. Technol. Water Supply* **14**, 618–625.

Mamadea, A., Loureiroa, D., Covasb, D., Coelhoa, S. T. & Amadoc, C. 2014 Spatial and temporal forecasting of water consumption at the DMA level using extensive measurements. *Procedia Eng.* **70**, 1063–1073.

Martini, A., Troncossi, M. & Rivola, A. 2017 Vibroacoustic measurements for detecting water leaks in buried small-diameter plastic pipes. *J. Pipeline Syst. Eng. Pract.* **8** (4), 1–10.

Martini, A., Rivola, A. & Troncossi, M. 2018 Autocorrelation analysis of vibro-acoustic signals measured in a test field for water leak detection. *Appl. Sci.* **8** (12), 1–15.

McIntosh, A. C. 2003 *Asian Water Supplies: Reaching the Urban Poor*. ADB, London, UK, pp. 59–65.

Michael, A., Ami, P., Mudasser, I. & Andrew, W. 2014 Water distribution system monitoring and decision support using a wireless sensor network. In: *14th ACIS International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing*. IEEE, Honolulu, pp. 641–646.

Miller, R. K., Pollock, A. A., Watts, D. J., Carlyle, J. M., Tafuri, A. N. & Yezzi Jrc, J. J. 1999 A reference standard for the development of acoustic emission pipeline leak detection techniques. *NDT & E Int.* **32**, 1–8.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD) 2017 *Statistical Yearbook of Urban Construction*. MHURD, China, pp. 3–5.

Muggleton, J. M. & Brennan, M. J. 2003 Leak noise propagation and attenuation in submerged plastic water pipes. *J. Sound Vib.* **278**, 527–537.

Porwall, S., Vijay, M., Jain, S. C. & Botre, B. A. 2018 A classification approach for monitoring and locating leakages in a smart water distribution framework. *CCIS* **827**, 418–429.

Sadeghioon, A. M., Metje, N., Chapman, D. & Anthony, J. C. 2014 Smart pipes: smart wireless sensor networks for leak detection in water pipelines. *J. Sensor Actuator Netw.* **3**, 64–78.

Sheng, J. & Jinghui, T. 2014 *Successful Reduction of non-Revenue Water (NRW). Engineering Asset Management – Systems, Professional Practices and Certification*. Springer, Cham, Switzerland, pp. 1055–1068.

Shifan, D., Siyu, M., Xiaowen, Z. & Shiqiang, Z. 2020 Integrated detection of a complex underground water supply pipeline system in an old urban community in China. *Sustainability* **1670** (12), 1–21.

Tao, T., Yan, H. X. & Xin, K. L. 2016 Pipe burst location analysis based on SCADA system pressure monitoring. *Water Technol.* **10**, 11–14.

Wu, Y., Liu, S., Wu, X., Liu, Y. & Gu, Y. 2016 Burst detection in district metering areas using a data driven clustering algorithm. *Water Res.* **100**, 28–37.

Yazdekhasti, S., Piratla, K. R., Atamturktur, S. & Khan, A. 2018 Experimental evaluation of a vibration-based leak detection technique for water pipelines. *Struct. Infrastruct. Eng.* **14** (1), 46–55.

Yu, H. L. 2017 *Study on the Vibration Characteristics Caused by Water Supply Pipeline Leakage*. Harbin Institute of Technology, China, pp. 1–10.

Zheng, L. & Kleiner, Y. 2012 State-of-the-art review of technologies for pipe structural health monitoring. *IEEE Sensors* **12**, 1987–1992.

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