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Experimental investigation into the influence of backfill types on the vibro-acoustic characteristics of leaks in MDPE pipe

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Abstract

Pipe leak location estimates are commonly conducted using Vibro-Acoustic Emission (VAE) based methods, usually using accelerometers or hydrophones. Successful estimation of a leak's location is dependent on a number of factors, including the speed of sound, resonance, backfill, reflections from other sources, leak shape and size. However, despite some investigation into some of the aforementioned factors, the influence of backfill type on a leak's VAE signal has still not been experimentally quantified. A limited number of studies have attempted to quantify the effects of backfill. However, all of these studies couple other variables which could be equally responsible for their observed changes in leak signal. There have been no controlled studies where one variable can be directly compared to one another (i.e. all variables remain constant, only changing backfill type). The aim of this paper is to better characterise the influence of backfill on a leak's VAE signal by individually isolating all variables. For the first time, this paper demonstrates the influence of backfill on leak VAE signal by keeping all other variables consistent. It was found that the backfill type had a strong influence on the frequency and amplitude of leak signals, which is likely to have a significant impact on the accuracy of leak location estimates.

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Keywords: Leak detection; water distribution systems; backfill; acoustics.

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1. Introduction

Leaking water distribution systems (WDS) cause both economic and environmental problems [1]. In some countries leakage can be as high as 50 %, especially in older distribution networks [2], where high water losses result in massive losses in revenue. Leakage has been reported by McMahon et al. [3] to cost the UK government £7bn annually due to street works and damage costs.

Nomenclature

τ_{delay}	Delay in arrival time (seconds) between sensor 1 and 2
d	Distance between sensor 1 & 2 (m)
c	Leak VAE signal wavespeed (m/s)
L_1, L_2	Distance from leak and sensors 1 and 2 (m)
$R_{x_1x_2}$	Cross correlation between leak signals
$E[\cdot]$	Expectation operator

Leaks are commonly found using the cross correlation technique. As the water discharges through the leak hole, it creates a Vibro-Acoustic Emission (VAE) which propagates along the pipe wall and through the water column. Accelerometers or hydrophones are normally placed at some distance from the leak (Fig. 1), recording the VAE produced by the leak, which is often termed the "leak signal". The leak location can then be found using Eq. 1, where d is the distance between the two accelerometers or hydrophones and c is the wavespeed of the leak signal:

$$L_1 = \frac{d - c\tau_{delay}}{2} \tag{1}$$

where τ_{delay} describes lag in arrival time between accelerometer 1 and 2, which is calculated from the peak in the cross correlation function using Eq. 2.

$$R_{x_1x_2} = E[x_1(t)x_2(t + \tau_{delay})], \tag{2}$$

where $E[\cdot]$ is the expectation operator. τ_{delay} is shown by:

$$\tau_{delay} = \tau_2 - \tau_{1.} \tag{3}$$

where τ_1 and τ_2 describes the arrival time at accelerometer 1 and 2 respectively.

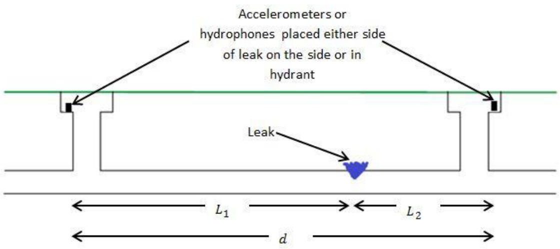


Fig. 1. Leak location schematic.

Although highly successful on metallic pipe, the cross correlation technique is less effective on plastic pipe as leak signals on plastic pipe tend to have a lower signal to noise ratio and do not propagate as far due to the viscoelastic nature of the pipe material and damping in the pipe wall [2]. Both Gao et al. [4] and Butterfield et al. [5] presented methods which can improve the cross correlation of leaks in MDPE pipe. Many others variables have been demonstrated to influence the leak signal, including leak flow rate [6]–[8], pipe material and diameter [9] and backfill type [10]. All of these aforementioned variables have been reported to influence a leak signal, which can in turn influence the accuracy of leak location estimates. Of the most commonly reported and most significant factors is that of leak flow rate, which has been reported to influence the amplitude of leak signals as leak flow rate increased [8], [7]. A similar phenomena was found in the gas industry where a number of authors found that increasing the flow rate through leaky gas pipes increased signal energy [11]–[13]. Both Kaewwaewnoi et al. [11], [12] and Chen et al. [13] were able to find good correlations between the signals Root Mean Square (RMS) of a sample containing N samples, $x[0], x[1], \dots . x[N-1]$ and leak flow rate:

$$RMS = \left(\frac{1}{2}\sum_{n=0}^{N-1} x[n]^2\right)^{0.5} \quad (4)$$

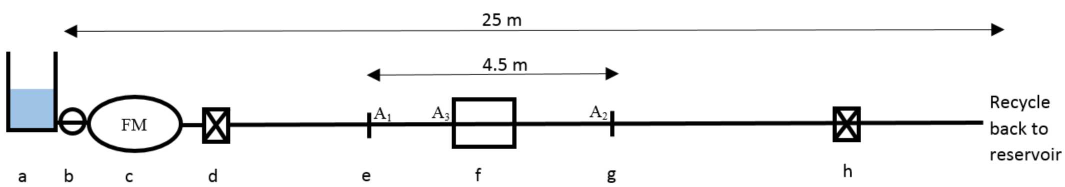
Kaewwaewnoi et al. [11], [12] continued to develop an equation which allows for the prediction of leak flow rate using signal RMS. However, it is unlikely this method would provide accurate estimates of leak flow rate in the water industry as leak flow rate has been shown to change when exposed to a surrounding medium [14], therefore estimates of leak flow rate using this method will be unreliable. The influence of backfill type has been investigated by only a few authors, but is often cited as a major factor influencing a leak signal. The leak signal is likely to be strongly affected by the backfill as the leak discharge pattern is influenced by the surrounding media, and some of the leak energy can be absorbed by surrounding media particles [15]. Van Zyle [16] reported that fluidisation of the surrounding media can occur in backfill surrounding a leaky pipe. Fluidisation can result in the mobilization of backfill particles when agitated by the leak, these in turn can create a sound as they mobilise and also by hitting the pipe wall, which is likely to interact with the leak signal. The surrounding media has also been reported to play a major role in the attenuation of signals, and can be due to the levels of compaction, soil type and degree of saturation and changes to the soils structure such as eroding the ground [17].

The influence of soil type and temperature on leak acoustics was investigated by Hunaidi and Chu [8]. The investigation took place on a buried test facility in Ottawa Canada, where frost penetrates to depths of 1.5 m. Hunaidi and Chu [8] found that at frequencies <10Hz, signals were similar in summer and winter, although there appeared to be a slightly higher attenuation rate of the lower frequency bands during the winter. A major reason for the attenuation of signals is radiation into the surrounding media [8]. The main frequency peak moved from 65 to 55 Hz in the summer. The reason for this shift in peak is unknown, however this may be due to a variation in the coupling between the soil and the hydrant (where the signals where measured) due to freezing [8]. Brennan et al. [18] analysed the influence of the surrounding media by burying a pipe in soil and air, reporting that there was no significant effect of the surrounding media on frequencies up to 500 Hz. However, they reported decreasing amplitudes away from the leak with increasing frequency on the buried pipe compared to a pipe in air, due to the transmission of energy into the ground. The main losses in this study appeared to be due to material damping in the pipe wall at frequencies up to 100 Hz. Brennan et al. [18] went on to bury the pipe in water, and found that there was a slight decrease in wavespeed and a small increase in attenuation. Moreover, Muggleton et al. [19]and Fuller and Fahy [20] demonstrated that the surrounding media had little influence on the axisymmetric wavenumber.

A study by Muggleton and Brennan [10] detailed the importance of understanding surrounding media and made comparisons between submerged pipes and pipes buried in soil, finding that submerged pipes attenuated less compared to that of pipes buried in soil. Although this study provided interesting results the study was limited by the fact that comparisons were made between two separate pipe rigs, and therefore the conditions could not be compared as the conditions are likely different (including the leak geometry, leak flow etc.). Pal et al. [15] also investigated leaks under sandy soil compared with leaks discharging to gravel, finding that there was no significant effect of backfill on the leak frequency response. However, in this study, there was no attempt to control other variables such as leak flow rate, which is likely to change depending on the backfill type and degree of compaction. Therefore, there appears to be a significant research gap; all previous studies that have attempted to experimentally quantify the effect of backfill on the leak signal have made no attempts to isolate or control the other variables (such as leak flow rate) which can contribute to a change in leak signal. These studies are therefore limited by this fact meaning that the conclusions cannot be verified. Therefore, the influence of backfill has not yet been experimentally determined. The overall aim of this study is to quantify the effect of backfill type on the VAE signal produced by the leak, by individually isolating all other variables which have been shown to influence the leak signal and therefore the conditions can be kept the same between conditions, with only the media type changing.

2. Methodology

This study was carried out on a 25 m length, 63 mm outer diameter, looped Medium Density Polyethylene (MDPE) pipe loop located at the University of Sheffield, UK (Fig. 2). Water was driven from an upstream tank by a 3.5 kW Wilo centrifugal pump (set at 10 rpm). Three accelerometers (sensitivity 10000 mV/g, PCB Piezotronics model 393B12) were connected to the pipe using a specially designed mounting in order for all of the accelerometer base to come into contact with the pipe wall, this was then attached to the pipe using an adhesive mounting wax. One accelerometer was placed next to the leak, and the other two accelerometers were placed approximately 2.25 m either side of the leak. Due to the equal spacing of the accelerometers, the theoretical time delay is approximately 0 seconds. Leaks of different shapes and sizes were created and inserted into a test section measuring 4.5 m. In the middle of the test section, a small box measuring 0.5 x 0.5 x 0.5 m was used in order to change the surrounding backfill. Backfill types used included the pipe submerged in water, geotextile fabric and gravel (8-10 mm gravel used in accordance with the British Standards for backfill [21]). The geotextile fabric (STABLEMASS 115) was used to represent a fully constrained porous media, which was also used by Fox et al. [14] who found this geotextile fabric to have a good representation of an unfluidised surrounding media. The leak wrapped in geotextile fabric was then submerged in water. The system pressure was changed by turning the downstream valve in order to change the system pressure and leak flow rate, to ensure the leak flow rate was the same for each leak type and therefore the influence of backfill on the leak signal can be determined. A minimum of 7 different leak flow rates were tested for each backfill type. Leak flow rate was recorded by measuring water coming out of an overflow in the test section box. The theoretical wavespeed for this test rig was calculated to be 331 m/s. Leak signals captured by accelerometers were captured by a National Instrument Data Acquisition board, into Labview and downloaded to a desktop computer. Signals were recorded for 2 minutes and averaged by processing using MATLAB software.



a. Reservoir	d. Upstream butterfly valve	g. Downstream flange plate	A_2. Accelerometer 2.
b. Pump	e. Upstream flange plate	h. Downstream gate valve	A_3. Accelerometer 3.
c. Flow meter	f. Test section box (0.5 x 0.5 x 0.5 m)	A_1. Accelerometer 1	

Fig. 2. Schematic of the test rig facility.

3. Results and analysis

3.1 Frequency response of the pipe system without a leak

Initially, the VAE of the pipe rig with no leak in place was analysed in order to create the reference data set for the pipe with a leak. Fig. 3 demonstrates the vibration of the pipe at 5, 8 and 11 m head. In the case of 5 and 8 m head, there appears to be no difference in frequency spectra. At 11 m head, a peak appears at round 318 – 416 Hz. It is believed this peak is related to valve screech as the leak downstream valve was closed to increase system pressure.

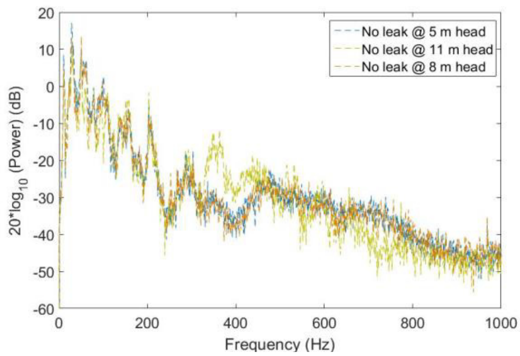


Fig. 3. Changes in frequency and amplitude without a leak at different pressures.

3.2 Frequency response with a leak in place

Fig. 4 demonstrates the frequency spectrum of a 3.5 mm round hole leak at 5 m head and 11 m head respectively with and without a leak. This corresponded to two leak flows, 5.45 l/min at 5 m head (weak leak), and 20.43 l/min at 11 m head (medium-strong leak). There was a distinct increase in amplitude for frequencies >214 Hz compared to the no leak scenario, suggesting that the cut on frequency for the leak was at 214 Hz.

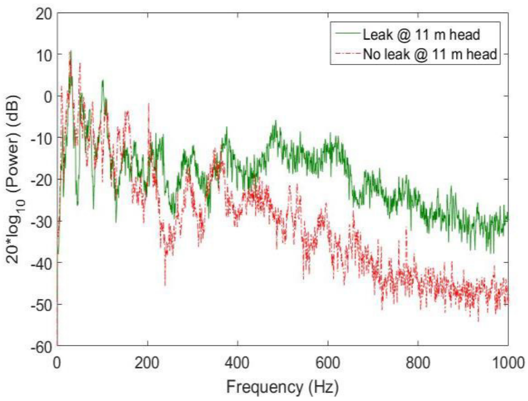


Fig. 4. Changes in frequency and amplitude of a 3.5 mm round hole.

3.3 Influence of leak flow rate

Leak flow rate was increased by turning the downstream valve, this increased system pressure in turn increasing leak flow rate. By keeping the leak sized fixed and changing the leak flow rate, it allows for the observation of the effect of leak flow on leak signal. The ratio of leak:no leak is plotted for three different leak flow rates in Fig. 5(a), with leak flow rates of 7.10, 11.62 and 20.43 l/min for a 3.5 mm round hole buried in gravel media. From Fig. 4 it can be observed that leak flow rate has a significant influence on the amplitude of leak signals, which appears to increase due to increased leak flow rate. However, the cut on frequency component of the leak signal does not appear to be effected by leak flow rate, with all leaks beginning at approximately 214 Hz. The influence of leak flow rate is also shown in Fig. 5(b). Leak flow rate and signal Root Mean Square (RMS) appeared to correlate well, achieving a Pearson's correlation coefficient of 0.954.

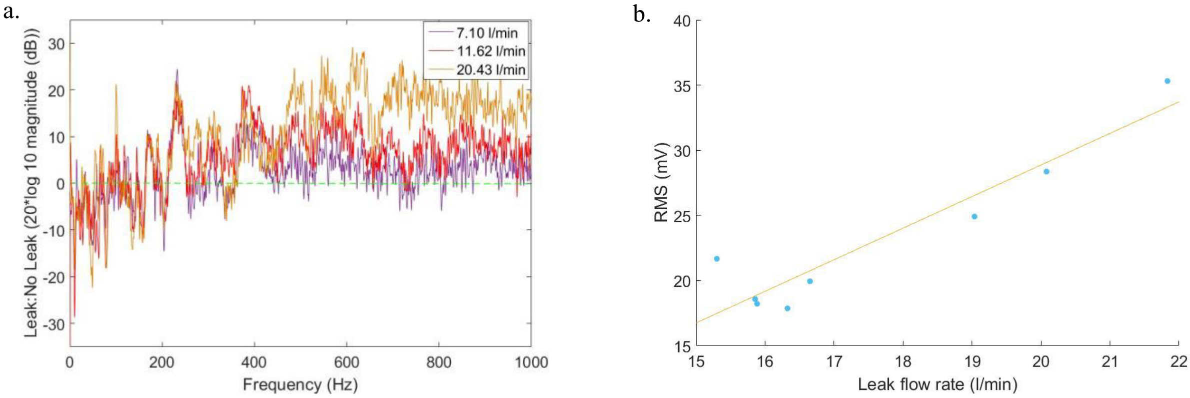


Fig. 5. Influence of leak flow rate on leak signal (a) frequency domain and (b) RMS vs leak flow rate.

3.4 Influence of backfill type

A series of tests were conducted to assess the influence of backfill. Backfill types investigated included geotextile fabric, gravel and submerged. Unlike previous research into this area, the flow rate was kept the same for each backfill type by manually adjusting the pressure to achieve the same leak flow. This allows for the isolation of the different variables and therefore the influence of backfill alone can be quantified. The results demonstrated in Fig. 6(a) suggest that background noise was mainly dominant <213 Hz for all backfill types. The cut on frequency for leaks did not change due to backfill, and was at about 214 Hz. The amplitude of leak signals was found to significantly be effected by backfill type, with the submerged sample having lower amplitude signals compared to gravel and geotextile. However, Fig. 6(a) demonstrates that certain frequencies were influenced by the backfill more than others, for example at 330 Hz the backfill type appears to have no effect on the signal. The trend of varying signal amplitude due to backfill type is shown further in Fig. 6(b), where the submerged pipe had lower RMS values compared to the other backfill, although RMS did increase for all backfill types and this trend was similar for all media types. Despite different RMS values, RMS was still found to correlate well with leak flow rate, achieving Pearson's correlation coefficient of 0.95 and 0.93 for the submerged and geotextile media respectively.

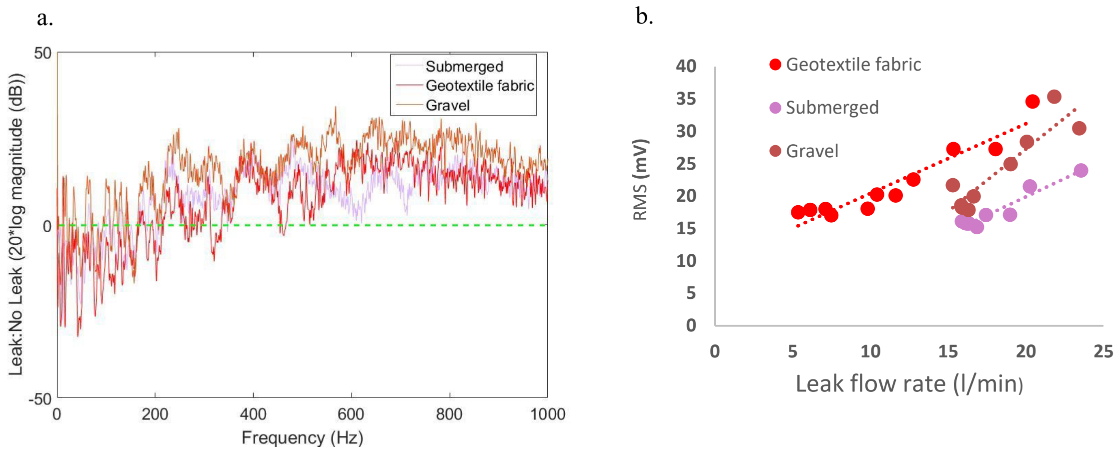


Fig. 6. Influence of backfill type on leak signal, recorded next to the leak: (a) frequency domain spectrum; and (b) RMS vs leak flow rate.

4 Discussion

This study assessed the influence of backfill types on the VAE signal produced by a 3.5 mm round hole in MDPE pipe at a variety of leak flow rates. Leak flow rate was found to increase the amplitude of leak signals, which was also found by many other authors ([6]–[8], amongst others). This study found good correlations between signal RMS and leak flow rate as leak amplitude increased with leak flow rate. It is likely the increase in amplitude is due to the fact that there is an increase in turbulence around the leak hole as more fluid exits the leak [11].

Evidently, the backfill type has a strong influence on the leak signal and this has been shown by a number of authors (see for example [10], [15], [19]). However, all previous studies are limited in their experimental design as they compare situations where more than one variable is changing (e.g. leak flow rate differs between backfill types), and therefore it is not possible to quantify whether the changing signal is due to a change in backfill or another variable. By isolating individual variables in this study, it was found that the backfill type had a strong influence on the spectrum of leak signals shown in the frequency domain and also by changing RMS values when the backfill type is changed. The change in RMS is possibly due to the fact that some of the leak energy is absorbed by different media particles [15], reducing the amplitude of some frequencies for different backfill types. However, some frequencies were less effected by backfill type. The submerged pipe tended to have the lowest amplitude signals compared to that of the geotextile and gravel media. This result differs to that of Muggleton and Brennan [10] who found higher amplitude signals discharging to submerged compared to a pipe buried in sandy soil. According to their study, leak energy radiated into soil more so than a submerged pipe, which was not the case in this study. However, the experiments conducted by Muggleton and Brennan [10] were conducted under two separate pipe rigs, with different leak flows and leak geometry and therefore the test results are not directly comparable.

5 Conclusions

This study represented an original experimental design which allowed for the isolation of different variables and therefore the effect of backfill could be revealed. It was found that the leak signal increased in amplitude as leak flow rate increased. However, when the leak flow rate is consistent across backfill types the amplitude of leak signals was strongly affected, suggesting that backfill influences the leak signal. Submerging the pipe reduced the amplitude of leak signals more so than compared to the geotextile fabric or gravel backfill. The results from this research are of high importance as the media type plays a strong role in defining the characteristics of the leak signal, which therefore will influence the accuracy of leak location estimates.

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References

[1] A. F. Colombo and B. W. Karney, "Energy and Costs of Leaky Pipes: Toward Comprehensive Picture," J. Water Resour. Plan. Manag., vol. 128, no. 6, pp. 441–450, 2002.
[2] F. Almeida, M. Brennan, P. Joseph, S. Whitfield, S. Dray, and A. Paschoalini, "On the Acoustic Filtering of the Pipe and Sensor in a Buried Plastic Water Pipe and its Effect on Leak Detection: An Experimental Investigation," Sensors, vol. 14, no. 3, pp. 5595–5610, 2014.
[3] W. McMahon, M. H. Burtwell, and M. Evans, "Minimising street works disruption: the real costs of street works to the utility industry and society, Tech. Rep. 05/WM/12/8," London, UK, 2005.
[4] Y. Gao, M. J. Brennan, and P. F. Joseph, "A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes," J. Sound Vib., vol. 292, no. 3–5, pp. 552–570, 2006.
[5] J. D. Butterfield, S. B. M. Beck, R. P. Collins, and C. D. Creusere, "Improving Leak Location Accuracy By Optimising the Time Delay Measurement of Acoustic Emission From Leaks in MDPE Pipe," in Proceedings of the International Congress of Sound and Vibration, 22., no. July 2015, pp. 12–16.
[6] J. D. Butterfield, R. P. Collins, and S. B. M. Beck, "Feature extraction of leak signals in plastic water distribution pipes using the wavelet transform," in Proceedings of the ASME 2015 International Mechanical Engineering Congress and Exposition, 2016, pp. 1–8.
[7] M. Pal, N. Dixon, and J. Flint, "Detecting & Locating Leaks in Water Distribution Polyethylene Pipes," World Congr. Eng., vol. II, 2010.
[8] O. Hunaidi and W. T. Chu, "Acoustical characteristics of leak signals in plastic water distribution pipes," Appl. Acoust., vol. 58, pp. 235–254, 1999.
[9] O. Hunaidi and A. Wang, "networks Acoustic Methods for Locating Leaks in Municipal Water Pipe Networks," pp. 1–14, 2004.
[10] J. M. Muggleton and M. J. Brennan, "Leak noise propagation and attenuation in submerged plastic water pipes," J. Sound Vib., vol. 278, no. 3, pp. 527–537, 2004.
[11] W. Kaewwaewnoi, A. Prateepasen, and P. Kaewtrakulpong, "Investigation of the Relationship Between Internal Fluid Leakage through a Valve and the Acoustic Emission Generated from the Leakage," Meas. J. Int. Meas. Confed., vol. 43, no. 2, pp. 274–282, 2010.
[12] W. Kaewwaewnoi, A. Prateepasen, and P. Kaewtrakulpong, "A Study on Correlation of AE Signals from Different AE Sensors in Valve Leakage Rate Detection," in ECTI transactions on Electrical Eng. Electronics, and Communications., 2007, no. August, pp. 113–117.
[13] P. Chen, P. S. K. Chua, and G. H. Lim, "A study of hydraulic seal integrity," Mech. Syst. Signal Process., vol. 21, no. 2, pp. 1115–1126, 2007.
[14] S. Fox, R. Collins, and J. Boxall, "Physical investigation into the significance of ground conditions on dynamic leakage behaviour," J. Water Supply Res. Technol. - Aqua, vol. 65, no. 2, pp. 103–115, 2016.
[15] M. Pal, "Leak detection and location in polyethylene pipes This item is held in Loughborough University ' s Institutional Repository (https://dspace.lboro.ac.uk/) and was harvested from the British Library ' s EThOS service (http://www.ethos.bl.uk/) ."
[16] J. E. van Zyl, M. O. a Alsaydalani, C. R. I. Clayton, T. Bird, and a Dennis, "Soil fluidisation outside leaks in water distribution pipes – preliminary observations," Water Manag., vol. 166, no. WM10, pp. 546–555, 2013.
[17] D. Reed, G. Read, and M. Price, "Discussion: the Influence of Mains Leakage and Urban Drainage on Ground Water Levels Beneath Conurbations in the Uk.," ICE Proc., vol. 86, no. 5, pp. 1019–1020, 1989.
[18] M. Brennan, P. Joseph, J. Muggleton, and Y. Gao, "The use of acoustic methods to detect water leaks in buried water pipes," Unpubl. Res. Rep., pp. 1–7, 2006.
[19] J. M. Muggleton, M. J. Brennan, and R. J. Pinnington, "Wavenumber Prediction of Waves in Buried Pipes for Water Leak Detection," J. Sound Vib., vol. 249, no. 5, pp. 939–954, 2002.
[20] C. R. Fuller and F. J. Fahy, "Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid," J. Sound Vib., vol. 81, no. 4, pp. 501–518, 1982.
[21] U. K. W. Industry, S. Materials, and F. O. R. Buried, "Water industry information and guidance note: Bedding and sidefill materials for buried pipelines," 2006.