Water Supply

Water Supply Vol 22 No 4, 4594 doi: 10.2166/ws.2022.120

Illegal connection detection in a viscoelastic pipeline using inverse transient analysis in the time domain

Ehsan Ebrahimi[a], Mahmood Shafai Bejestan[b,*] and Babak Aminnejad[c]

[a] Department of Civil Engineering, Kish International Branch, Islamic Azad University, Kish Island, Iran
[b] Department of Water and Environmental Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
[c] Department of Civil Engineering, Roudehen Branch, Islamic Azad University, Roudehen, Iran
*Corresponding author. E-mail: m-shafaeibejestan@scu.ac.ir

ABSTRACT

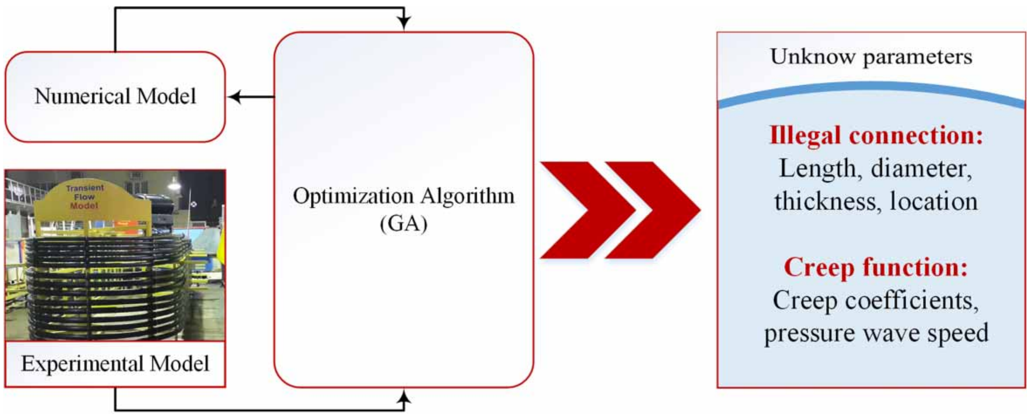
Illegal connection (IC) in water supply systems and water network wastes water as well as energy and reduces water quality, which has negative technical and economic effects on water management. Transient-based defect detection is a powerful method applied in water pipelines. This paper investigates the efficiency of the transient-based inverse transient analysis (ITA) method in estimating the characteristics of ICs in the viscoelastic water supply system in the time domain. To better evaluate this method, an experimental transient model was developed using polyethylene pipelines (with a length of 158 meters and a nominal diameter of 2 inches). In the first step, the hydraulic transient solver was calibrated in the calibration approach of dynamic parameters of pressure wave speed and pipe wall viscoelasticity. Then, the sensitivity of the ITA method to the spatial step of the method of characteristics and signal sample size was assessed. Finally, the efficiency of the ITA method was evaluated for several experiments with different transient intensities and a noisy signal. The results indicated that the accuracy for locating the IC was higher than the accuracy for the IC's length.

Key words: illegal connection detection, inverse transient analysis, time domain, viscoelastic pipeline

HIGHLIGHTS

- Development of a hydraulic transient solver to simulate viscoelastic pipeline with different boundary conditions include illegal connection.
- Development of an experimental transient model with an illegal connection.
- Analysis of the accuracy of inverse transient analysis (ITA) to detection of illegal connection.
- Evaluation of the effect of noise on the accuracy of illegal detection.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The lives of about three billion people depend on urban water supply systems. However, these vital systems have drawbacks and inefficiencies due to aging. Water injected into water supply pipelines claims significant energy and costs in the collection stages in dam reservoirs, transfer to cities and villages, monitoring and treatment, storage and pumping, and finally transmission and distribution among consumers. Thus, many economic and technical damages will be inflicted on the operating companies by wasting water. Water losses usually occur due to various causes such as depletion of network components and corrosion of pipes, connection failures, illegal connections, shocks caused by construction, plus occurrence of waterhammer, drifts, landslides, etc. According to the World Bank, $ 15 billion of water is lost worldwide each year. Also, 29 billion cubic meters of water worth $ 2 billion are lost annually in Asia (World Bank Group 2016).

Water loss wastage is divided into two general categories: real and apparent (Lambert & Hirner 2000; Lambert 2003). One of the main sources of apparent water loss is the illegal connection (IC) or water theft in water supply systems and water distribution networks. This water volume loss is withdrawn of the water pipeline systems without being measured and paid for. This problem is widespread in developing countries and Europe (Meniconi *et al.* 2011).

So far, various methods have been proposed to identify defects in water pipelines based on steady and unsteady flow. Compared to a steady flow, transient flow is more efficient at detecting defects (Colombo *et al.* 2009). In transient-based defect detection methods, a periodical pressure wave is initially propagated throughout the pipe system. The pressure response of the pipe system is then collected in one place (usually at the transient valve location). Analysing the collected pressure signal makes it possible to discuss defects (leakage, blockage, air pocket, or IC) in the pipe system. Transient-based research can be divided into three general categories; frequency-domain methods (Duan *et al.* 2010; Gong *et al.* 2013; Duan 2016; Kim 2018; Wang & Ghidaoui 2018; Al-Tofan *et al.* 2020; Wang *et al.* 2020; Keramat *et al.* 2021), time-domain methods (Covas 2003; Vıtkovsky *et al.* 2007; Keramat *et al.* 2019; Waqar *et al.* 2019; Zouari *et al.* 2019), and analysis based on signal processing (Al-Shidhani *et al.* 2003; Ferrante & Brunone 2003; Keramat & Duan 2021; Waqar *et al.* 2021).

Meniconi *et al.* (2011) applied transient-based techniques to determine IC's location and sizes. In this study, transient signal analysis was based on wavelet analysis. They proposed a simple relation for detecting the IC characteristics reliably. Duan & Lee (2016) numerically tested the ability of a transient-based method for detecting IC in the frequency domain. They first developed a frequency response function for a pipeline system with IC, and then the IC was found to cause shifts in the system's resonant frequencies. Their results indicated that the accuracy for locating the IC is higher than for its size.

Over the last two decades, the application of polymer pipes has been increasing due to their advantages. Because of fluid and viscoelastic pipe wall interaction, the transient flow modelling of polymer pipes differs that of from elastic pipes. Viscoelastic properties cause deformation and increase the damping in these pipes compared to elastic pipes (Covas 2003). On the other hand, a review of the research background shows that no study has been conducted on the inverse transient analysis (ITA) capability to detect IC in the viscoelastic pipeline in the time domain. Accordingly, this research has been performed to cover this topic.

The main purpose of this study is to evaluate the efficiency of the ITA method for detecting the IC in a viscoelastic transmission pipeline system. Initially, the developed numerical model calibration for simulating the viscoelastic pipeline system has been discussed in detail. Then, the capability of this model was evaluated based on IC in several experimental samples. Finally, the capability of the proposed method to detect IC was assessed based on the noisy signal.

2. MATERIALS AND METHODS

This section first describes the IC detection process using the ITA. The second part describes the 1D equations governing the transient flow in viscoelastic pipelines. In the third part, the experimental system is presented in detail, and finally, the calibration process of the developed numerical model is presented.

2.1. ITA methodology

The ITA is a famous methodology for defect (e.g., leakage, blockage, IC) detection in water pipeline systems (Liggett & Chen 1994; Kapelan *et al.* 2003). This methodology consists of three general sub-sections: numerical model, laboratory or field data, and an optimization algorithm. In this method, the optimization algorithm estimates the unknowns of the piping system by minimizing the difference between on-site measured and numerical computational data (commonly pressure signal).

In this research, the pressure signal was collected behind the transient valve through fast closing it in a pipe system with IC to apply ITA for IC detection. In the second part, a genetic optimization algorithm was used whose objective function was the least-square error (LSE). Then, a hydraulic transient solver was developed, including viscoelasticity of the pipe wall and the boundary condition of IC. The numerical model was implemented by introducing the main pipeline system's geometric parameters and assuming that there is an inactive viscoelastic IC in the pipeline with unknown characteristics. The numerical model includes unknown parameters, including pressure wave speed and creep function coefficient of the main pipe plus IC, as well as location, length, thickness, and diameter of IC. The optimization algorithm initially generated these unknown parameters in a population of 100. They were gradually optimized by reducing the difference between the pressure signal behind the transient valve in the experimental model and the corresponding one in the numerical model through applying the mutation and crossover on the initial generated population.

Note that since the diameter and thickness of the pipe are not continuous variables and have nominal values, these two variables of the pipe characteristics are introduced as binary (according to the industrial standard table) to the optimization algorithm. Also, the data collected have some noise due to environmental conditions. Thus, before introducing the experimental data to the ITA model, their noise was removed using a Butterworth low-pass filter (with order 2 and normalized cut off frequency 0.2). The flowchart of the ITA used in this study is displayed in Figure 1.

2.2. Equations governing

The one-dimensional continuity and momentum equations governing the transient flow in a polymer pipe are as follows (Covas *et al.* 2005; Keramat *et al.* 2020):

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}+\frac{2a^2}{g}\frac{d\varepsilon_r}{dt}=0 \tag{1}$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{dQ}{dt}+(h_{fs}+h_{fu})=0 \tag{2}$$

where H is the instantaneous hydraulic head, Q denotes the instantaneous discharge, A represents pipe cross-sectional area, g shows the gravity acceleration, a is the pressure wave speed, $\varepsilon_r$reflects the retarded strain, x is the coordinate along the pipe axis, t stands for the time, and h_{fs} and h_{fu} are the steady and unsteady friction losses per unit length, respectively.

Darcy–Weisbach equation ($h_{fs}=(f/D)(Q|Q|/2gA^2)$ is used for calculation of steady friction losses, where f is Darcy–Weisbach coefficient, and D is pipe's internal diameter.

Total strain (ε) can be expressed as an instantaneous-elastic strain (ε_0) plus a retarded-viscous strain (ε_r). For a specific continuous stress $\sigma(t)$ on the polymer pipe under small strain conditions, according to the Boltzmann principle, the total strain can be defined as follows:

$$\varepsilon(t)=J_0\,\sigma(t)+\int_0^t\sigma(t-t')\,\frac{\partial J(t')}{\partial t'}\,dt' \tag{3}$$

where J_0 is the instantaneous creep compliance function, $J(t')$ denotes the creep compliance function at time t'.

According to Figure 2, the creep compliance function for a viscoelastic solid material can be described using the generalized Kelvin–Voigt model as follows (Aklonis *et al.* 1972):

$$J(t)=J_0+\sum_{k=1}^{N_{KV}}J_k(1-e^{-t/\tau_k}) \tag{4}$$

where J is the creep compliance function, J_k denotes the creep of the spring of the Kelvin–Voigt k-element, defined as $J_k=1/E_k$, τ_k represents the retardation time of the dashpot of k-element, defined as $\tau_k=\mu_k/E_k$, E_k is the modulus of elasticity of the spring of k-element, μ_k reflects the viscosity of the dashpot of the k-element, and N_{KV} is the number of the Kelvin–Voigt element.

In this study, the set of differential equations was solved using the method of characteristics (MOC) (Keramat *et al.* 2020).

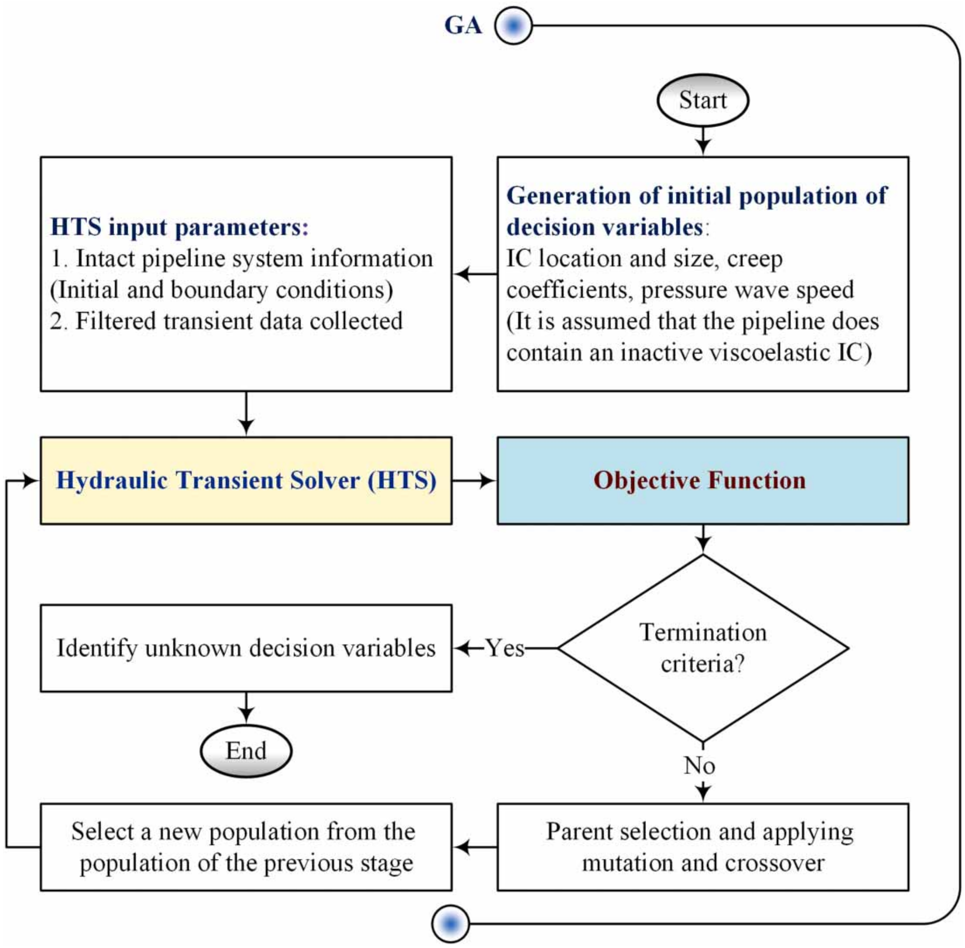


Figure 1 | Flowchart of ITA for IC detection.

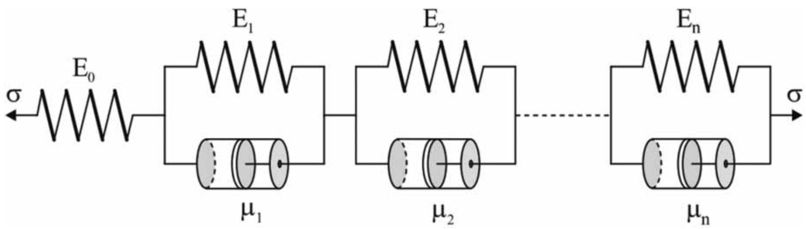


Figure 2 | Generalized Kelvin–Voigt model.

2.3. Experimental facility

The experiments of this research were performed at Shahid Chamran University of Ahvaz, Iran. The experimental model consists of the high-density polyethylene HDPE (PE100 and NP16 bar) pipeline. The main pipeline's total length was 158 m, and its internal diameter and thickness were 5.05 cm and 6.5 mm, respectively. Also, the length of IC was 24.2 m for all experiments, with its internal diameter and thickness being 3.025 cm and 5.0 mm, respectively. It was constructed in upwardly sloped loops. All pipes were fixed to a metal structure (6 m × 1.5 m) with metal brackets, about 1 m spacing. The experimental facility included a centrifugal pump and a pressure vessel (650 L) at the upstream end. Two ball and globe valves were used in the pipeline downstream end to generate transient event and flow control, respectively. The transient event was generated by a ball valve's complete and fast closure. The discharge was measured as the volumetric method. The pressure data were

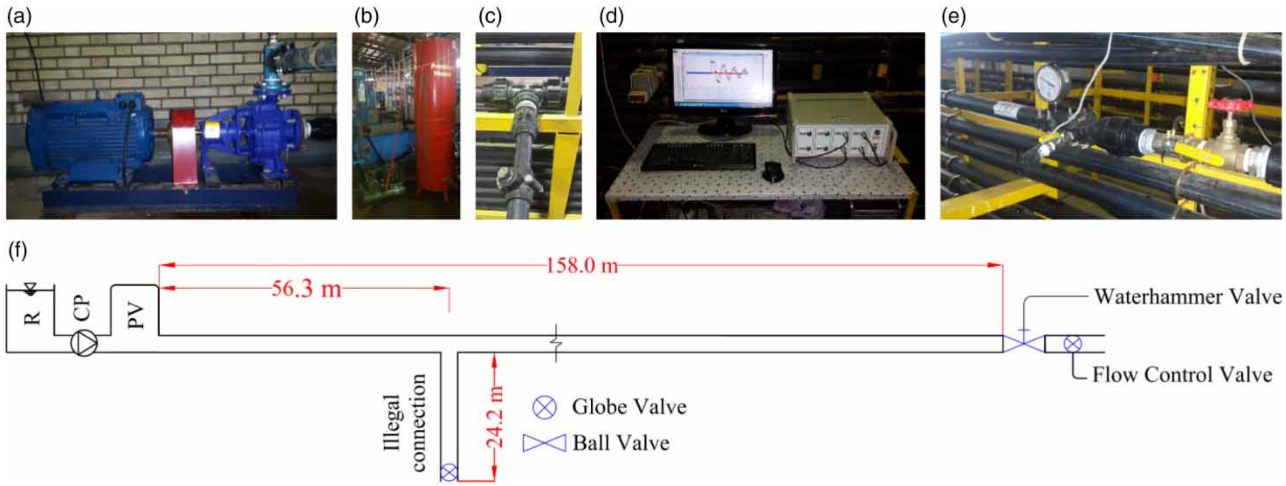


Figure 3 | Experimental setup, (a) centrifugal pump (CP), (b) pressure vessel (PV), (c) IC, (d) data acquisition system (data logger and computer), (e) downstream valves, and (f) 2D schematic of transient model of reservoir-pipe-valve system with IC.

collected using WIKA S-10 pressure transmitters with a measurement range of 0–16 bar and an accuracy of 0.1%. The sampling rate of collected data was 1,000 Hz. A schematic view and several pictures of the experimental model are displayed in Figure 3. The main measurement sections are placed at the transient generating ball valve and on the pressure vessel upstream of the pipelines.

2.4. Numerical model calibration

Calibration of intact reservoir-pipe-valve polymer pipeline with known upstream reservoir constant level and downstream valve manoeuvre boundary conditions include creep function of the pipe wall, pressure wave speed, and friction coefficients. In this paper, the collected upstream boundary pressure of the pipeline was introduced in the numerical model. Also, the downstream boundary condition was the ball valve employed to generate a transient event. In all experimental tests, the closing time of the valve was less than $2L/a$, and it fell in the category of fast closing.

The steady-state friction coefficients in the laminar flow conditions were calculated based on the Hagen–Poiseuille relation ($f = 64/Re$). According to Covas (2003) and Rahmanshahi *et al.* (2018), for polymer pipes with a smooth wall, the flow regime is smooth turbulent. Hence, for turbulence flow conditions, the steady friction coefficients were directly calculated from the Blasius relationship ($f = 0.316Re^{-0.25}$).

According to Duan *et al.* (2010), unsteady friction for pipe systems at the scale of the pipe system of this research can be ignored. Furthermore, according to Duan *et al.* (2010) and Brunone *et al.* (2011), the viscoelastic effect is dominant over unsteady friction, allowing unsteady friction to be neglected. Their analytical results demonstrated that the unsteady friction effect is more critical in polymer pipe systems with short pipe lengths and small pipe diameters. The pipeline system of this research is in large-scale classification, and its pressure response is of a low-frequency type. Thus, the hydraulic transient solver was implemented, neglecting unsteady friction.

A creep compliance function typically describes the mechanical behaviour of the viscoelastic pipes that can be determined using laboratory tests. However, due to uncertainty of material properties and anisotropy, the experimentally determined creep function cannot accurately describe the behaviour of the viscoelastic pipes under operating conditions. In the operation phase of an existing system, in addition to the mentioned uncertainties, the creep function highly depends on the axial and circumferential constraints of the system along with the stress time-history of the pipe, which cannot be accounted in the laboratory creep tests (Covas *et al.* 2005). Similar to the creep function, the pressure wave speed in polymer pipes is also a function of the creep function factors. Thus, calibration of these challenge parameters requires sensitivity analysis, which is discussed in the results section. Thus, all system's unknown parameters were a, τ_k and j_k of the main pipeline along with IC, plus IC location and sizes (length, diameter, and thickness).

3. RESULTS AND DISCUSSION

This section is divided into two general sections. The first part investigates the sensitivity of determining the IC characteristics to different parameters. The second part deals with the ability of the ITA to determine the characteristics of IC for new experiments with different transient intensities and noisy signals assessed.

3.1. Sensitivity analysis of IC detection

In addition to IC and pipe system characteristics, the accuracy of ITA for IC detection in the pipeline is related to transient solver accuracy, spatial step of the MOC, the sample size of the pressure signal, transient intensity, collected data, and system's characteristics uncertainty, and accuracy of the optimization method. In this study, the first four items are evaluated.

3.1.1. Creep function and pressure wave speed calibration approach

When simulating the viscoelastic pipeline the creep function of pipe wall and pressure wave speed is estimated. In addition, modelling them separately or simultaneously with other unknown parameters is another challenge. For this purpose, two scenarios have been implemented to investigate these challenges. Furthermore, two different experimental data sets were applied for this challenge. The first test was carried out on a simple pipeline system without IC (intact pipeline). The second test was performed on the same pipeline with an IC located at 56.3 m from the upstream boundary with a length of 24.2 m. In both experiments, the downstream flow rates were 1.18 l/s. Figure 4 depicts the pressure signals of both experiment tests adjusted upstream of the transient valve.

In the first scenario, the pressure wave speed and the creep function of the main pipeline are obtained based on the intact pipe test, where these parameters are used to detect the IC in the second test in ITA. Thus, in the first scenario, the ITA's unknowns are only characteristics of the IC (pressure wave speed, creep function, length, diameter, thickness, and location). However, in the second scenario, the pressure wave speeds, the creep functions of the main pipeline and IC, as well as the IC characteristics are calibrated simultaneously based on the second experiment (pipeline with IC). In this scenario, the unknowns of ITA include the main pipeline and IC's pressure wave speeds plus creep functions and the IC characteristics (length, diameter, thickness, and location). According to Covas (2003) and Rahmanshahi *et al.* (2018) as well as the preliminary analysis, three Kelvin–Voigt elements are sufficient for modelling this pipeline.

Figure 5 displays the ITA results for the first experimental test (intact pipeline) involving comparison of the numerical and experimental pressure signal, creep coefficients, retardation times, and creep function, respectively. These calibrated parameters were used to detect the IC in the first scenario. The results of both scenarios are illustrated in Figure 6. Figure 6(a) compares experimental and numerical pressure signals at the transient valve location. The creep coefficients for both scenarios are shown in Figure 6(b). The first scenario employed the main pipeline's creep coefficients and retardation times from the intact pipeline. Thus, only IC's creep coefficient was calibrated. However, the main pipeline and IC's pressure

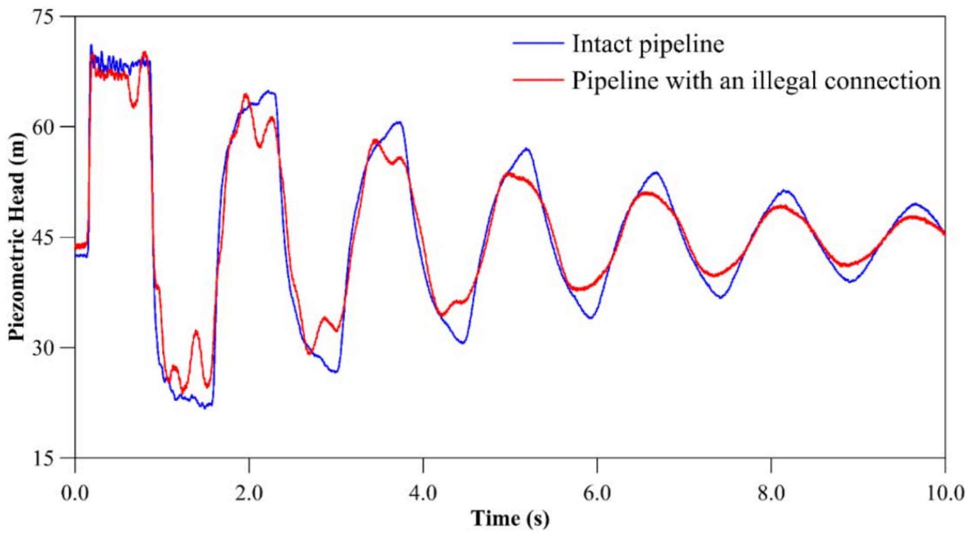


Figure 4 | Comparison of pressure signal in the intact pipeline and pipeline with an IC.

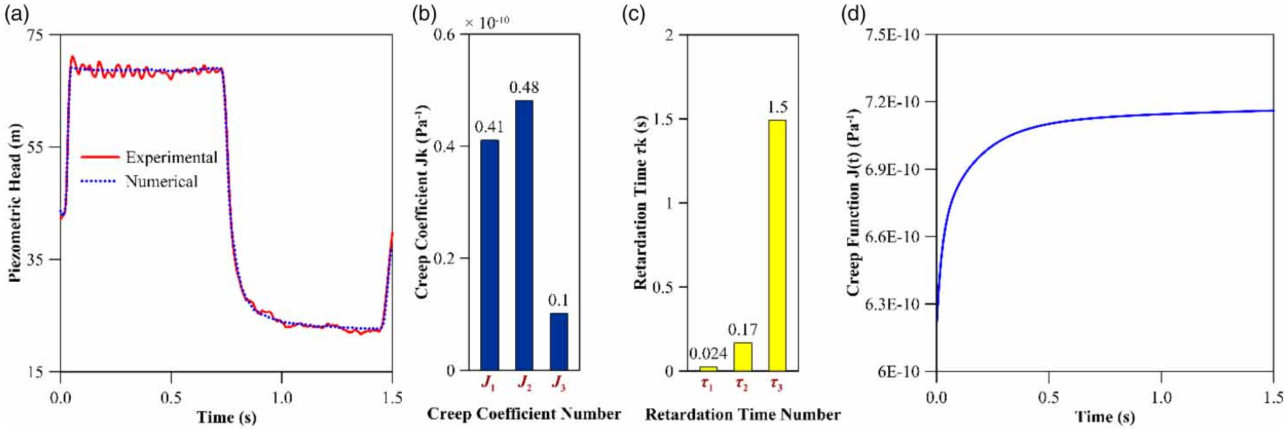


Figure 5 | (a) Numerical and measured piezometric heads at transient valve location, (b) creep function coefficients, (c) creep function retardation times, and (d) creep function.

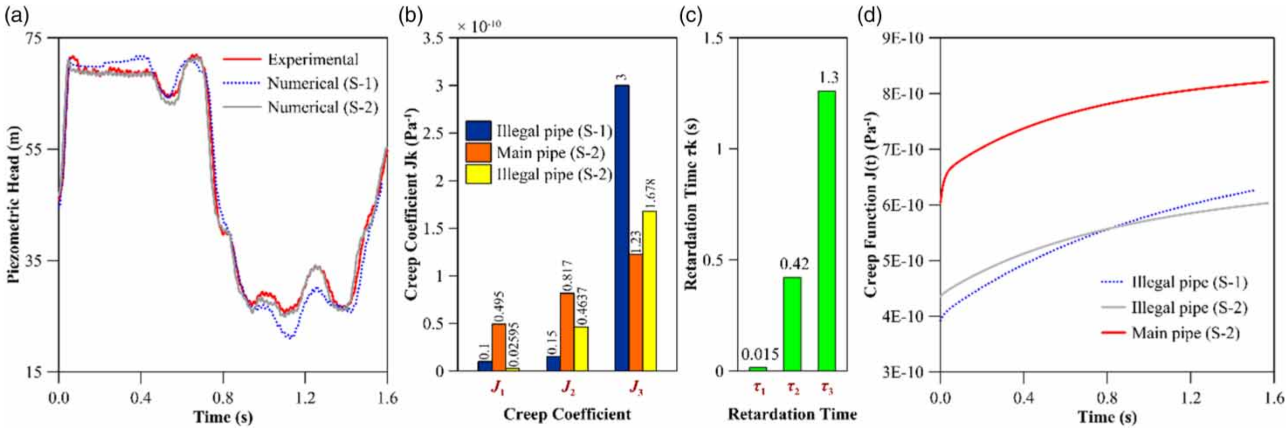


Figure 6 | Comparison of (a) piezometric heads at transient valve location, (b) creep function coefficients, (c) creep function retardation times, and (d) creep function, for both scenarios.

wave speeds as well as creep coefficients were calibrated simultaneously with IC characteristics for the second scenario. Figure 6(c) reveals the retardation times of the second scenario. Note that in this research, the retardation times have been considered to be the same for the main pipeline and IC. Figure 6(d) shows the creep function for both scenarios.

Figure 7 illustrates the results for both scenarios. The first scenario had discrepancies with location and length errors equalling 23.97 and 13.18%, respectively. For the last scenario, although the IC length error has not changed much (22.77%), its location has been carefully determined with an error of about 1.3%, equivalent to 2 meters of the pipeline system. Note that in determining the defect in pipe systems, the location of the defect is more important than its other characteristics.

In conclusion, according to Covas *et al.* (2005) and Rahmanshahi *et al.* (2018) and similar to the last scenario, for IC detection in the operation stage, the creep function and pressure wave speed should be calibrated based on on-site collected transient data (commonly transient pressure data) and simultaneously with other decision variables in any ITA modelling. Thus, for each ITA modelling in this study, the decision variables included creep coefficients (τ_k, j_k) and pressure wave speed (a) of the main pipeline and IC, plus length, diameter, thickness, and location of IC.

3.1.2. Evaluating the spatial step

To highlight the effect of the spatial step on the detection of IC characteristics, at this stage, the sensitivity of the ITA to the spatial step was assessed with six different spatial steps, ranging from 0.64 to 5.41% of the main pipeline's length. This analysis was performed on the same data set applied in the previous step. The details of these simulations are outlined in Figure 8.

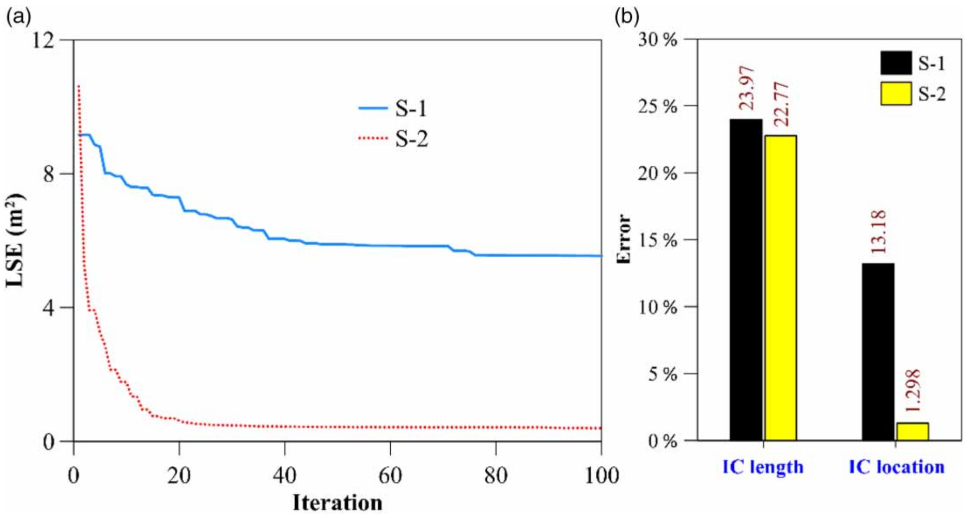


Figure 7 | (a) Convergence process of ITA model, and (b) location and length error, in both scenarios.

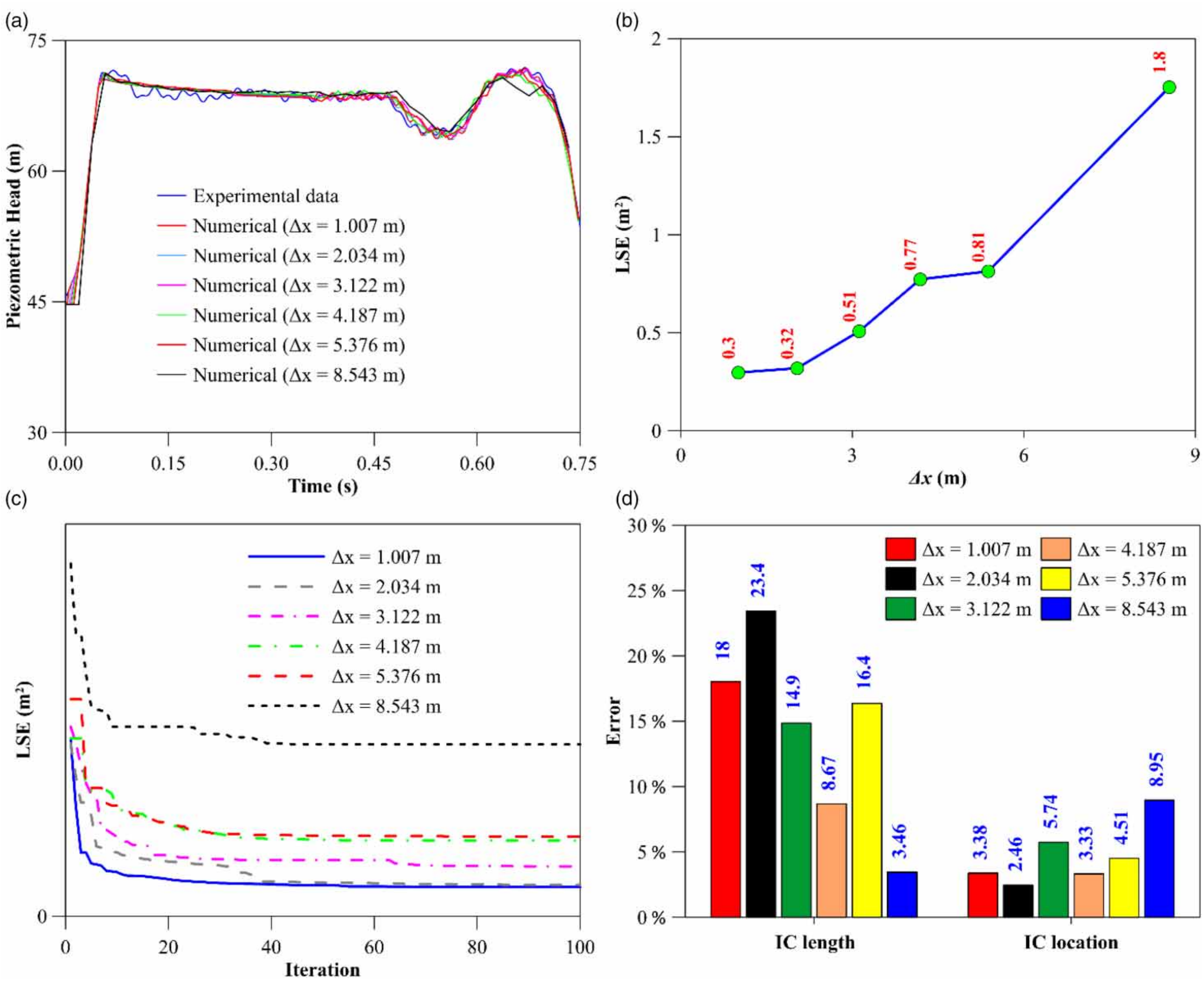


Figure 8 | Comparison of (a) piezometric heads at transient valve location, (b) minimum LSE, (c) convergence process of ITA model, and (b) location and length error, at different spatial steps.

Figure 8(a) compares the pressure signal for the six different simulations with laboratory data. The results show that all six models of pressure signal shape are similar to laboratory data. Figure 8(b) and 8(c) indicate the minimum value along with the process of minimizing the objective function for different spatial steps, respectively. The results show that LSE grows with increasing the spatial step, and the convergence of the ITA slows down. The location and length error values of these simulations are revealed in Figure 8(d). The length error in these six models is between 3.46 and 23.4%, and the value of location error is between 2.46 and 8.95%. The model with a larger spatial step has a minimum length error and a maximum location error. Since our priority is to determine the location of the IC, in the rest of this research, the modelling was done with a spatial step of 2.034 meters.

3.1.3. Sample size assessment

In this subsection, the appropriate pressure signal sample size was evaluated to detect the IC characteristics. For this purpose, four sample sizes (0.5*T*, *T*, 2*T*, and 3*T*) were analysed (*T* = theoretical period of the pressure wave). Figure 9(a) exhibits the pressure signal and its different sample sizes. The ITA errors for all four sample sizes are shown in Figure 9(b). The IC location error is between 0.61 and 7.3% for all sample sizes, with the slightest IC location error corresponding to the half-period. In polymer pipes, over time, the pressure wave is severely dampened. Thus, defective reflection is more pronounced in the initial cycles, and applying the ITA with a smaller sample size gives better results. Also, the IC length error is between 13.13 and 21% for all sample sizes. Due to the importance of IC location, the ITA was simulated with a half-cycle sample size.

3.2. Validation of ITA for IC detection

In the calibration stage, the approach of estimating the creep function and pressure wave speed as well as the appropriate sample size and spatial step was determined in this research experiments. In the validation stage, two goals are pursued. First, the accuracy of the ITA for different experiments with different flow rates will be evaluated, and then the sensitivity of this method to noise will be assessed.

3.2.1. Different transient intensities

This part evaluates the efficiency of ITA for new experiments with different intensities. For this purpose, the accuracy of ITA for four experiments is assessed with Reynolds numbers of 17153.31 ($Q = 0.68$ l/s), 34054.4 ($Q = 1.35$ l/s), 42277.9 ($Q = 1.676$ l/s), and 60314.1 ($Q = 2.391$ l/s). The errors of the length and location of the IC are depicted in Figure 10(a) and 10(b), respectively. The IC length error in all four experiments is less than 16%, and its location error is less than 3%. As the transient intensity (*Q*) increases, the magnitude of both errors decreases. At stronger transient events, the reflection effect is greater, thus enhancing the ability of ITA to detect the IC. Note that in order not to damage the pipe system, the transient event generated should be less intense. Thus, the optimal transient event for fault identification can be the subject of future studies.

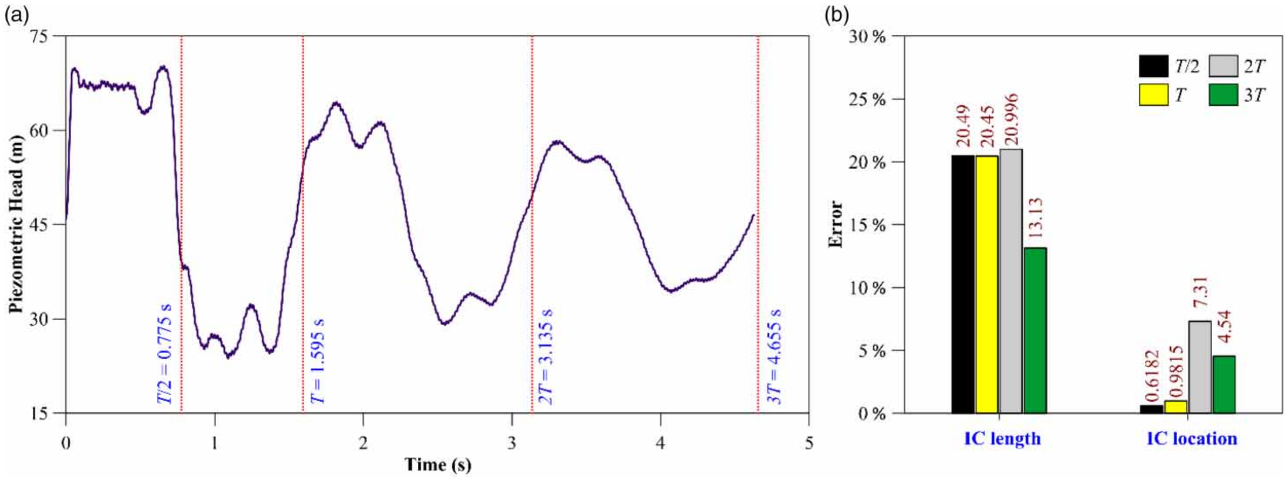


Figure 9 | (a) Pressure signal, and (b) IC location and length errors, for all four sample sizes.

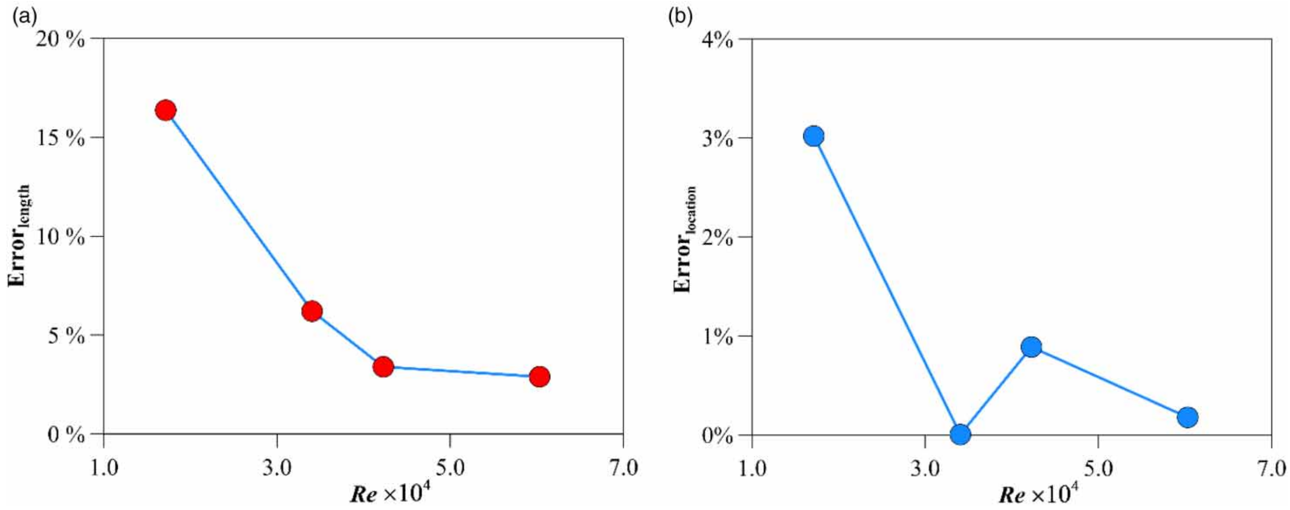


Figure 10 | Validation of ITA for different transient intensity.

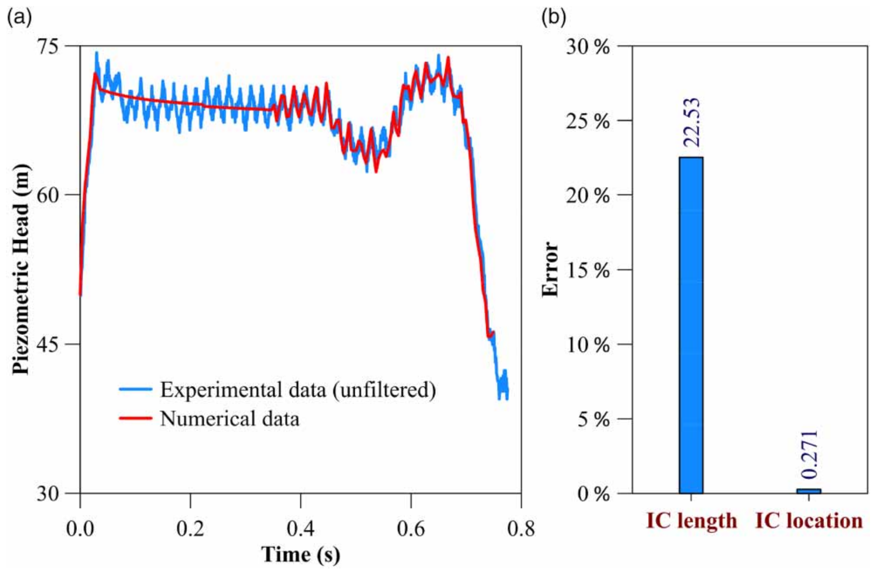


Figure 11 | (a) Comparison of experimental and numerical pressure signals, and (b) IC length and location errors, for a noisy signal.

3.2.2. Performance of ITA to detect IC for noisy signals

Due to random noise in the real signals, IC detection is subject to a degree of uncertainty. In this section, the performance of the ITA for noise signals was examined. For this, the unfiltered first half-period of the experiment signal with a flow rate of 1.18 l/s was used in the ITA model. According to previous tests, the IC of this test was located at 56.3 away from upstream of the pipeline. Figure 11 compares the experimental and numerical pressure signal as well as the estimated IC location and length errors. The results show that the ITA points to IC locations with an error of 0.271% and IC length with 22.53%. Hence, despite the noise in the signal, the ITA detected the location of the IC with a reasonable accuracy.

4. CONCLUSIONS

The transient-based ITA has been studied as an efficient method in calibration and detecting defects in the water pipe system over the last two decades. This study used experimental data to investigate the efficiency of this method in detecting IC characteristics in the viscoelastic water main. In the calibration stage, initially the best approach for estimating the creep function of pipe wall and pressure wave speed was evaluated. Then, sensitivity of the model to the spatial step and pressure signal sample size was investigated. Next, the efficiency of the calibrated model was assessed for new experiments with different transient event intensities and the noisy signal. The hydraulic transient solver incorporates only viscoelasticity of the pipe wall and can model the transient flow in polymer pipelines with IC. The results revealed that the transient-based ITA successfully detected IC's location and sizes when the IC, creep function of the pipe wall, and pressure wave speed were simultaneously calibrated. The nominal number of the pipe, which was introduced to the optimizer model as binary, was chosen correctly in the entire modelling. Evaluation of the sample size used for the ITA showed that the IC location with the half-cycle signal was accurately determined. Modelling with different spatial steps indicated that the spatial step-to-length ratio of about 1.3% gives acceptable results. Overall, the accuracy for locating the IC was higher than for its length. IC location and length errors were lower than 3 and 16% for all validation tests, respectively. Finally, evaluation of the ITA for a noisy signal showed that this method could detect the IC with an accuracy close to the filtered signal with location and length errors of 0.271 and 22.53%, respectively. In conclusion, it can be stated that the detection of IC with the ITA is satisfactory and can be enhanced by combining this method with other local techniques such as acoustic equipment.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Aklonis, J. J., MacKnight, W. J. & Shen, M. 1972 *Introduction to Polymer Viscoelasticity*. Wiley-Interscience – John Wiley & Sons, Inc., New York, USA.

Al-Shidhani, I., Beck, S. B. M. & Staszewski, W. J. 2003 Leak monitoring in pipeline networks using wavelet analysis. *Key Engineering Materials* **245–246**, 51–58.

Al-Tofan, M., Elkholy, M., Khilqa, S. & Chaudhry, H. 2020 Leak detection in liquid pipelines using lower harmonics of pressure oscillations. *Journal of Pipeline Systems Engineering and Practice* **11** (4), 04020033.

Brunone, B., Cacciamani, M. & Meniconi, S. 2011 Unsteady friction and visco-elasticity in pipe fluid transients. *Journal of Hydraulic Research* **49** (3), 402–403.

Colombo, A. F., Lee, P. & Karney, B. W. 2009 A selective literature review of transient-based leak detection methods. *Journal of Hydro-Environment Research* **2** (4), 212–227.

Covas, D. 2003 *Inverse Transient Analysis for Leak Detection and Calibration of Water Pipe Systems- Modelling Special Dynamic Effects*. PhD Thesis. Imperial College of Science, Technology, and Medicine, University of London, London, UK.

Covas, D., Ramos, H., Graham, N. & Maksimovic, C. 2005 Application of hydraulic transients for leak detection in water supply systems. *Water Science and Technology Water Supply* **4** (5–6), 365–374.

Duan, H. F. 2016 Transient frequency response based leak detection in water supply pipeline systems with branched and looped junctions. *Journal of Hydroinformatics* **19** (1), 17–30.

Duan, H. F. & Lee, P. J. 2016 Transient-based frequency domain method for dead-end side branch detection in reservoir pipeline-valve systems. *Journal of Hydraulic Engineering* **142** (2), 04015042.

Duan, H. F., Ghidaoui, M. S., Lee, P. J. & Tung, Y. K. 2010 Unsteady friction and visco-elasticity in pipe fluid transients. *Journal of Hydraulic Research* **48** (3), 354–362. .

Ferrante, M. & Brunone, B. 2003 Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis. *Advances in Water Resources* **26** (1), 107–116.

Gong, J., Zecchin, A. C., Simpson, A. R. & Lambert, M. F. 2013 Frequency response diagram for pipeline leak detection: comparing the odd and even harmonics. *Journal of Water Resources Planning and Management, ASCE* **140** (1), 65–74.

Kapelan, Z., Savic, D. & Walters, G. 2003 A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. *Journal of Hydraulic Research, IAHR* **41** (5), 481–492.

Keramat, A. & Duan, H. F. 2021 Spectral based pipeline leak detection using a single spatial measurement. *Mechanical Systems and Signal Processing* **161**, 107940.

Keramat, A., Wang, X., Louati, M., Meniconi, S., Brunone, B. & Ghidaoui, M. S. 2019 Objective functions for transient-based pipeline leakage detection in a noisy environment: least square and matched-filter. *Journal of Water Resources Planning and Management, ASCE* **145** (10), 04019042.

Keramat, A., Fathi-Moghadam, M., Zanganeh, R., Rahmanshahi, M., Tijsseling, A. S. & Jabbari, E. 2020 Experimental investigation of transients-induced fluid-structure interaction in a pipeline with multiple-axial supports. *Journal of Fluids and Structures* **93** (2020), 102848.

Keramat, A., Karney, B., Ghidaoui, M. S. & Wang, X. 2021 Transient-based leak detection in the frequency domain considering fluid–structure interaction and viscoelasticity. *Mechanical Systems and Signal Processing* **153**, 107500. .

Kim, S. H. 2018 Development of multiple leakage detection method for a reservoir pipeline valve system. *Water Resources Management* **32** (6), 2099–2112.

Lambert, A. 2003 Assessing non-revenue water and its components: a practical approach. *Water* **21** (August), 50–51.

Lambert, A. & Hirner, W. 2000 *Losses From Water Supply Systems: Standard Terminology and Recommended Performance Measures*. IWA The Blue. IWA, London, pp. 1–13.

Liggett, J. A. & Chen, L. C. 1994 Inverse transient analysis in pipe networks. *Journal of Hydraulic Engineering* **120** (8), 934–955. .

Meniconi, S., Brunone, B., Ferrante, M. & Massari, C. 2011 Transient tests for locating and sizing illegal branches in pipe systems. *Journal of Hydroinformatics* **13** (3), 334–345.

Rahmanshahi, M., Fathi-Moghadam, M. & Haghighi, A. 2018 Leak detection in viscoelastic pipeline using inverse transient analysis. *Journal of Water and Wastewater* **29** (5), 85–97. (In Persian)

Vıtkovsky, J. P., Lambert, M. F., Simpson, A. R. & Liggett, J. A. 2007 Experimental observation and analysis of inverse transients for pipeline leak detection. *Journal of Water Resources Planning and Management, ASCE* **133** (6), 519–530.

Wang, X. & Ghidaoui, M. S. 2018 Pipeline leak detection using the matched-field processing method. *Journal of Hydraulic Engineering* **144** (6), 04018030.

Wang, X., Waqar, M., Yan, H. C., Louati, M., Ghidaoui, M. S., Lee, P. J. & Karney, B. 2020 Pipeline leak localization using matched-field processing incorporating prior information of modeling error. *Mechanical Systems and Signal Processing* **143**, 106849..

Waqar, M., Louati, M. & Ghidaoui, M. S. 2019 Leak localization using time reversal technique. In *Proc., 38th IAHR World Congress*, Panama City, Panama. Vol. 10.

Waqar, M., Louati, M., Wang, X. & Ghidaoui, M. S. 2021 Model-free matched field processing for condition assessment of pressurized pipes. *Journal of Water Resources Planning and Management* **147** (10), 04021066.

World Bank Group 2016 High and Dry: Climate Change, Water, and the Economy. World Bank, Washington, DC.

Zouari, F., Blasten, E., Louati, M. & Ghidaoui, M. S. 2019 Internal pipe area reconstruction as a tool for blockage detection. *Journal of Hydraulic Engineering* **145** (6), 04019019.

First received 24 November 2021; accepted in revised form 22 February 2022. Available online 3 March 2022