# Leak detection by inverse transient analysis in an experimental PVC pipe system

Alexandre Kepler Soares, Dídia I. C. Covas and Luisa Fernanda R. Reis

## ABSTRACT

Leakage reduction in water supply systems and distribution networks has been an increasingly important issue in the water industry since leaks and ruptures result in major physical and economic losses. Hydraulic transient solvers can be used in the system operational diagnosis, namely for leak detection purposes, due to their capability to describe the dynamic behaviour of the systems and to provide substantial amounts of data. In this research work, the association of hydraulic transient analysis with an optimisation model, through inverse transient analysis (ITA), has been used for leak detection and its location in an experimental facility containing PVC pipes. Observed transient pressure data have been used for testing ITA. A key factor for the success of the leak detection technique used is the accurate calibration of the transient solver, namely adequate boundary conditions and the description of energy dissipation effects since PVC pipes are characterised by a viscoelastic mechanical response. Results have shown that leaks were located with an accuracy between 4–15% of the total length of the pipeline, depending on the discretisation of the system model.

**Key words** | calibration, hydraulic transients, inverse models, leak detection, plastic pipes

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## INTRODUCTION

Real losses in water supply systems are associated with pipe breaks and leaks resulting from physical deterioration and inadequate operation of such systems as well as high operating pressure levels. Efficient location of leaks is thus required in order to effectively control water losses and to quickly repair the system. The analysis of hydraulic transients can be particularly useful for pipe calibration and for leak detection purposes. System observation for such analysis can reveal a substantial amount of information concerning physical properties and the integrity of the system, since water hammer waves are affected by different features and phenomena of the system, including leaks.

This research work focuses on inverse transient analysis (ITA) for leak detection and calibration of water distribution system models. ITA consists of the minimisation of the sum of the square errors between measured state variables (pressures or flow rates) and calculated state variables by using a hydraulic transient solver. Optimisation algorithms based on both global and local search techniques have been used (i.e. genetic algorithms, GA, and the Levenberg–Marquardt algorithm, LM). Data were obtained from experiments carried out in a complex multi-pipe system composed of PVC pipes with and without simulated leaks. The methodology has been applied in

two steps: first, ITA was used for calibration of the creep function using transient data collected for both leak and non-leak tests, and afterwards was applied for leak detection using leak test data. Good results in terms of leak detection have been obtained with a hydraulic transient solver incorporating the viscoelastic behaviour of the pipe material, considering that the classical theory is extremely imprecise for plastic pipes (e.g. polyethylene, PE, and polyvinyl chloride, PVC), which are characterised by viscoelastic rheological behaviour (Ferry 1970; Aklonis & MacKnight 1983). The application of ITA has shown that leaks can be located and sized with an accuracy corresponding up to 4% of the total length of the pipeline, despite the presence of data errors (noise in the pressure transient signal) and errors in calibrated viscoelastic parameters of the hydraulic transient solver, the optimisation method capability of ascertaining the best solutions and the complexity of boundary and internal conditions of the system. In this way, the major potential of the technique presented in this paper is for the detection of large bursts or opened pipe branches in complex water transmission mains composed of plastic pipes (PVC) and several features such as pipe branches, check valve, ball valves, pumps, pipe displacements and changes in pipe diameters.

## LEAK DETECTION IN WATER PIPE SYSTEMS

Several techniques for leak detection in pressurised hydraulic systems have been presented in the literature using different methods based on time, frequency or inverse analysis of transient pressure signals (Liggett & Chen 1994; Vítkovský *et al.* 2000, 2007; Brunone & Ferrante 2001; Mpesha *et al.* 2001; Stoianov *et al.* 2001; Kapelan *et al.* 2003; Covas *et al.* 2005*a*; Lee *et al.* 2005; Ferrante *et al.* 2007). In spite of the fact that methods based on frequency domain analysis and on observations of wave speed travelling time generally present efficient results in terms of computational time as well as discretisation issues, the extension of these methods to complex boundary conditions and pipe systems with different topologies, such as closed loop systems, remains unsolved. With regard to frequency response methods, the linearised water hammer equations require to be solved under more general boundary conditions. On the other hand, inverse

transient models based on hydraulic transient solvers and different optimisation techniques (inverse transient analysis – ITA) are conceptually independent of the system topology, as long as all boundary conditions and system properties (e.g. attenuation and dispersion of pressure waves) are described by an adequately calibrated solver. However, knowing the system well can be an advantage but, in some cases, this may not be sufficient and can severely affect the success of ITA (Vítkovský *et al.* 2007).

Inverse transient analysis was initially proposed by Liggett & Chen (1994) for leak detection and calibration of water network models. This method is based on the minimisation of mean square errors between measured and calculated state variables (pressures or flow rates). The authors used pipe friction factors and effective leak areas (product of the discharge coefficient and the actual leak area) as decision variables, and the LM search method was used to solve the minimisation problem. Vítkovský *et al.* (2000) introduced GA as the search method to solve the inverse problem. Although slower than LM, GA carry out a more robust search on a population of solutions, increasing the chance to converge to a global optimum. Recently, global–local hybridisations have been proposed in the literature (Kapelan *et al.* 2003; Soares *et al.* 2003), which have proven to be more efficient in parameter calibration than conventional search methods. By using an iterative two-step procedure, Tucciarelli *et al.* (1999) evaluated leakage losses in different areas of a pipe network during steady state flows. The first step is estimation of the parameters in the network simulation model (loss factors and loss exponent) by means of the maximisation of a likelihood function. The second step is optimisation of the openings of the valves included in the network in order to enhance the different response of the network with respect to the water loss and the load in each node.

Practical applications of current leak detection techniques have been a hard task as experienced by Covas *et al.* (2004) and Stephens *et al.* (2004, 2005). Savic *et al.* (2009) pointed out some reasons why inverse transient analysis has not yet been widely accepted by practitioners, such as the problems with pressure wave speed calibration and wave reflections in complex distribution systems, cost of field measurement, lack of commercially available software incorporating calibration routines and system security.

## INVERSE MODEL

The indirect approach to solve the inverse problem of parameter identification is set as the minimisation of weighted mean square errors between observed and calculated piezometric heads, as follows:

$$\min_{Z} OF = \sum_{t=1}^{DT} \left\{ \sum_{j=1}^{n^H} \left[ (H_{t,j} - H_{t,j}^*)^2 / \left( \sum_{i=1}^{n^H} H_{t,i}^* / n^H \right)^2 \right] \right\} \quad (1)$$

where $OF$ = objective function; $DT$ = number of time steps of observed hydraulic transient event (the first time instance used in the optimisation, $t = 1$, refers to the beginning of the transient event); $H$ = piezometric head calculated by the hydraulic transient solver; $H^*$ = observed piezometric head (collected data in the experimental facility); $n^H$ = number of pressure observation locations in the system; and $Z$ = decision variable vector composed of unknown calibration parameters. Although the measurements and the calculations do not occur at the same time $t$, linear interpolations were carried out in the measurements so that these correspond to the same $t$ as the calculations (i.e. the time step of the measurements is not equal to the time step in the numerical simulations).

### Hydraulic transient solver

Equations that describe the one-dimensional transient-state flows in viscoelastic closed conduits are the momentum and continuity equations (Equations (2) and (3), respectively). Since the flow rate and piezometric head (dependent variables) in transient flows are functions of time and space (independent variables), these equations are a set of two hyperbolic partial differential equations (Chaudhry 1987; Almeida & Koelle 1992; Wylie & Streeter 1993; Covas *et al.* 2005b):

$$\frac{1}{A}\frac{dQ}{dt} + g\frac{\partial H}{\partial x} + gh_f = 0 \quad (2)$$

$$\frac{dH}{dt} + \frac{a_0^2}{gA}\frac{\partial Q}{\partial x} + \frac{2a_0^2}{g}\frac{d\epsilon_r}{dt} = 0 \quad (3)$$

where $x$ = coordinate along the pipe axis; $t$ = time; $H$ = piezometric head; $Q$ = flow rate; $a_0$ = celerity or elastic wave speed (dependent on the fluid compressibility, and on

the physical properties and external constraints of the pipe); $g$ = acceleration due to gravity; $A$ = pipe cross-sectional area; $\epsilon_r$ = retarded strain component (in viscoelastic pipes the total strain can be decomposed into an instantaneous-elastic strain and a retarded strain); and $h_f$ = head loss per unit length ($h_f = fQ|Q|/2DA^2$ in turbulent conditions, in which $f$ = Darcy–Weisbach friction factor and $D$ = pipe inner diameter). These equations assume: pseudo-uniform velocity profile; linear viscoelastic rheological behaviour of the pipe wall; one-phase, homogenous and compressible fluid, though with negligible changes in density and temperature; uniform and completely constrained from axial or lateral pipe movement.

The set of differential Equations (2) and (3) can be solved by the Method of Characteristics (MOC). Using a rectangular computational grid (Figure 1) and neglecting convective terms (the fluid velocity is negligible compared to the elastic wave speed), these equations can be solved numerically by the following scheme:

$$C^{\pm}: (H_{i,t} - H_{i\mp1,t-\Delta t}) \pm \frac{a_0}{gA}(Q_{i,t} - Q_{i\mp1,t-\Delta t}) \pm a_0\Delta t.h_f$$

$$+ \frac{2a_0^2 \Delta t}{g}\left(\frac{\partial \epsilon_r}{\partial t}\right)_{i,i\mp1} = 0 \quad (4)$$

valid along $\Delta x/\Delta t = \pm a_0$, respectively. In these equations, the retarded-strain time derivative (fourth term) cannot be directly calculated and requires further numerical discretisation. Covas (2003) presents the basis for calculating these terms.

When subjected to a constant stress, plastic materials present an instantaneous elastic strain followed by a gradual time-dependent retarded strain. The ratio between the retarded strain $\epsilon_r(t)$ and the load $\sigma_0$ describes the creep compliance function of the material, $J(t) = \epsilon_r(t)/\sigma_0$. In this
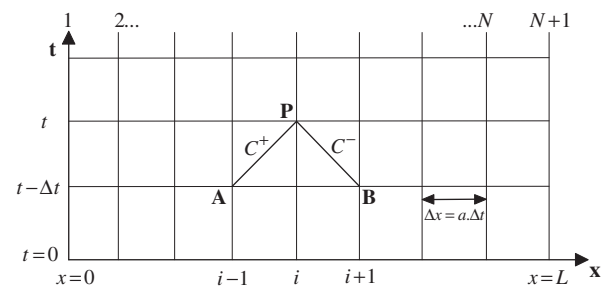


**Figure 1** | Characteristic grid with specified time intervals.

paper, the creep function is described by a mathematical expression which is incorporated in the hydraulic transient equations by the generalised Kelvin–Voigt mechanical model of a viscoelastic solid. This model is a combination of elements (springs and dashpots) that numerically describe the rheological response of viscoelastic solids (Aklonis & MacKnight 1983):

$$J(t) = J_0 + \sum_{k=1}^{N_{KV}} J_k(1 - e^{-t/\tau_k}) \tag{5}$$

where $J_0 =$ creep compliance of the first spring defined by $J_0 = 1/E_0$; $E_0 =$ Young's modulus of elasticity of the pipe; $J_k =$ creep compliance of the spring of the Kelvin–Voigt $k$ element defined by $J_k = 1/E_k$; $E_k =$ modulus of elasticity of the spring of the $k$ element; $\tau_k =$ retardation time of the dashpot of the $k$ element, $\tau_k = \mu_k/E_k$; $\mu_k =$ viscosity of the dashpot of the $k$ element; and $N_{KV} =$ number of Kelvin–Voigt elements. Parameters $J_k$ and $\tau_k$ are fitted to the creep-compliance experimental data or determined by inverse calculation.

To complete the solution at any time instant, it is necessary to introduce appropriate boundary conditions, specifying additional equations at the ends of each pipe. With regard to leak detection simulations, leakage is simulated at nodal points in the characteristic grid as an additional virtual "non-pipe element" (Koelle *et al.* 1996). The leaking node is solved using two compatibility equations and an orifice equation that describes the leak:

$$Q_L = C_d A_0 \sqrt{2g(H_L - z_L)} \tag{6}$$

where $Q_L =$ leaking flow; $C_d A_0 =$ effective leak area (product of the discharge coefficient $C_d$ and the actual leak area $A_0$); $H_L =$ piezometric head at the leak; and $z_L =$ elevation of the leak point. A leak can be located by determining the best decision variables vector in terms of the effective leak areas considering a previous number of candidate nodes for leak locations.

## Optimisation models

In order to solve the inverse problem (Equation (1)), a two-step procedure is applied for calibration of viscoelastic parameters. First, an effective global search method (Genetic Algorithm, GA) is used to determine the best decision variable vector $Z$, composed of $\tau_k$ and $J_k$ groups ($Z = \{\tau_k, J_k\}$; $k = 1$ to $N_{KV}$). Once $\tau_k$ values are established, a local search method (Levenberg–Marquardt) is used to verify the best solution in terms of creep coefficients $J_k$ ($Z = \{J_k\}$; $k = 1$ to $N_{KV}$). Therefore, problems associated with the GA slow convergence (large number of objective function evaluations) and with the local search method converging to local minima can be significantly reduced. For the leak location simulations, GA are used to determine the best decision variable vector in terms of the effective leak areas ($Z = \{C_d A_{0i}\}$; $i = 1$ to 7).

Computationally simple, genetic algorithms are global search methods that seek the solution in the whole of the decision variable space: however, they lack the ability to perform a local search due to limitations in the operators used (e.g. mutation). The advantages of GA over traditional search methods include the fact that they retain a population of well-adapted sample points, thus increasing the chance of reaching the global optimum. Moreover, these algorithms consider probability rules for the transition from one set of trial solutions to the next, and they have the flexibility of admitting many types of objective functions without requiring the continuity and existence of their derivatives.

The Levenberg–Marquardt algorithm is an iterative technique that locates a local minimum of a function that is expressed as the sum of squares of several nonlinear real-valued functions. It has been widely used for dealing with data-fitting applications, such as nonlinear Least Square Error (LSE) problems. When the current solution is close to a local minimum, LM exhibits fast convergence, once the initial values are accurate enough. Actually, LM is a pseudo-second-order method which means that it works with only function evaluations and gradient information (Jacobian matrix) but it estimates the Hessian matrix using the sum of outer products of the gradients. The main disadvantages of the LM method are the need for the calculation of gradients (which, in the current case, have been calculated numerically) and matrix inversion as part of the update process.

## EXPERIMENTAL DATA COLLECTION

An extensive experimental programme has been carried out in the Experimental Hydraulic Circuit (EHC) composed of

PVC pipes, assembled at the Department of Hydraulic and Sanitary Engineering, São Carlos School of Engineering, Brazil. This experimental facility has 11 rectangular loops, with a total length of 203.20 m and nominal diameters between 50 and 100 mm. The EHC has a set of 16 ball valves and 16 gate valves that can be closed or opened to change the topology of the system as well as to control the flow and to generate transient events. Leaks can be simulated by 12 side discharge valves. There is a ball valve of 1.5 inches (3.8 cm) diameter at the downstream end to generate a water hammer. Pipes are rigidly fixed to a metal frame fixed to a vertical wall (fixing restraints spaced 1.5 m, approximately). PVC was chosen due to the low cost of the pipes, and their easy and fast assembly.

The supply system includes two parallel centrifugal pumps with powers of 0.7355 kW and 3.68 kW, and with a swing check-valve located immediately downstream. At the upstream end, there is an elevated tank with a constant level of 5 m above ground which supplies water to the system.

The data acquisition system is composed of: 3 electromagnetic flow meters (to measure steady-state flow), 9 volumetric flow meters installed downstream of the side-discharge valves to measure steady state leak flow, 16 pressure transducers; an acquisition board and a microcomputer.

In this research work, transient tests were carried out in a simplified configuration of the network as presented in Figure 2, in order to reduce uncertainties and the complexity of boundary and interior conditions. The neglected pipes of the experimental facility are represented by thin dashed lines whereas the used part of the system is represented by thick continuous lines.

Considering the system configuration presented in Figure 2, all pipes have 75 mm inner diameter, except pipes near the electromagnetic flow meters and pipe branches, which have 101 and 53 mm inner diameters, respectively. The pipe has a cross-section reduction to 15 mm inner diameter between the centrifugal pump and the check valve. The simplified system has a total length of 97.20 m between the elevated tank and the downstream end ball valve: 18.10 m from the elevated tank to centrifugal pump, 67.30 m from pump to ball valve and 11.80 m along branches.

Pressure data were collected at five locations (Figure 2): P06, P02 (at the leak location) and P01 located, respectively, at 7.20, 32.40 and 46.10 m downstream from the pump, P05 located immediately upstream from the pump and P07 located immediately upstream of the ball valve (67 m from the pump).

During the experiments, flow was measured for steady state conditions and pressure data were collected during transient events with a frequency of 1000 Hz. The air bubbles were released by two mechanisms: first, by allowing water to flow continuously in the system during one day; second, by letting the system be pressurised during one day, after some time the air dissolves in the water and is released. Two transient tests are analysed in this paper corresponding to the following steady state turbulent conditions: (i) $Q_0 = 1.84$ L/s, $Q_L = 0.84$ L/s; and (ii) $Q_0 = 2.47$ L/s, $Q_L = 0.73$ L/s (in which $Q_0 =$ the upstream end flow and $Q_L =$ the leak flow).
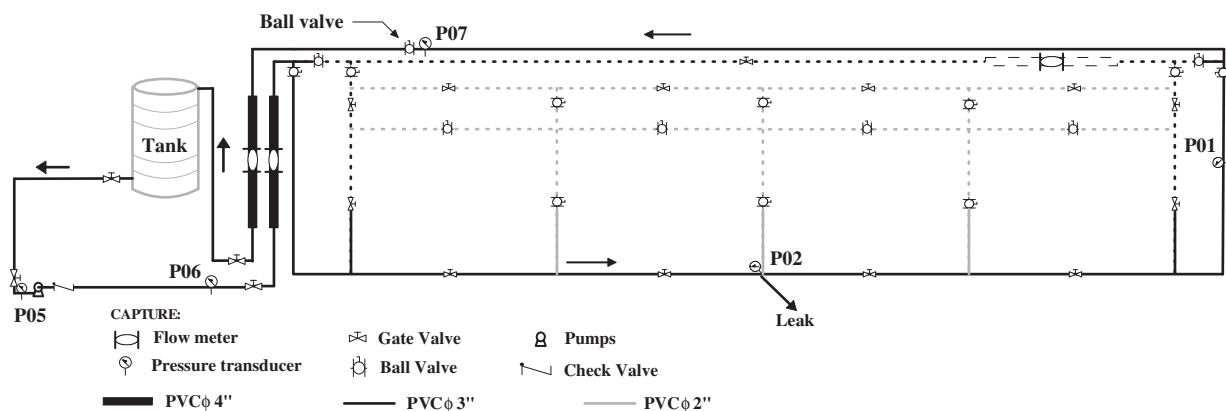


**Figure 2** | Experimental hydraulic circuit (EHC): simplified system configuration (thick continuous line) and neglected pipes (thin dashed line).

## MODEL CALIBRATION

The ITA is used to locate induced leaks in the EHC pipe system using observed transient pressure data. For the successful application of ITA, parameters of the viscoelastic transient solver are determined independently and before the leak detection simulations using non-leak test data. Creep functions numerically calculated by means of ITA calibration (for leak and non-leak cases) and experimentally determined by mechanical creep tests are presented.

### Creep calibration for the non-leak case

The inverse model was used to determine the creep compliance function $J(t)$ for the non-leak case. Elastic wave speed was estimated at 460 m/s ($E_0 = 3.069$ GPa; $J_0 = 0.3258$ GPa$^{-1}$; $\Delta x = 0.45$ m and $\Delta t = 9.7826 \times 10^{-4}$ s). The defined $\Delta t$ and $\Delta x$ were used for all simulations. The first choice was $\Delta x$ (0.45 m) in order to cover all different trunks (suction line, discharge line, pipe branches) and to have a constant wave speed everywhere in the system. For example, each vertical pipe branch has 1.80 m (5 pipe branches with 50 mm and 75 mm inner diameters – Figure 2), which corresponds to 5 pipe sections in the MOC equally spaced at 0.45 m. Thus the length of all trunks in the simulated system was not changed and the Courant stability condition was maintained. The corresponding $\Delta t$ was calculated after the wave speed has been calibrated based on the viscoelastic model and on the transient pressure data collected ($a_0 = 460$ m/s). Its value was not 1/1000 s as the time step in the measurements, but measurements were interpolated linearly in order to avoid asynchronous evaluations in the objective function $OF$ (Equation (1)).

Parameters $J_k$ and $\tau_k$ are first estimated by using a GA search method considering only transient pressure data at location P07 (immediately upstream from the ball valve). Concerning the simplified system that has been analysed in this study, the conclusion was that five pressure transducers were not necessary for calibration and leak detection purposes (Soares 2007). Additionally, the facility allows other configurations of the network for which the transducers are necessary not only for leak detection analyses but also for hydraulic transient investigations. The decision was to present in this paper the facility as it is with all the potential measurements that can be carried out.

Ten distinct initial populations of solutions (with different random seeds) represented by real strings were run using an elitist (30%) generational GA, linear scaling of fitness, stochastic remainder sampling (SRS) as the selection scheme, uniform arithmetic crossover with 70% probability and gene-by-gene Gaussian mutation with 1% probability. One hundred generations were used for each GA evaluation. Several initial numerical simulations were run to find the best number of Kelvin–Voigt elements. Combinations of one, two and three elements were tested to better describe the creep compliance function of PVC pipes. The optimal number of Kelvin–Voigt elements was obtained by using a single element. Figure 3 depicts the variation of the minimum objective function value for each simulation (10 random seeds) and the respective optimal values obtained for the viscoelastic parameters $\tau_k$ and $J_k$. The best group of decision variables was determined by using random seed 9000 (see table in Figure 3) corresponding to $\tau_1 = 0.058$ s and $J_1 = 0.0252$ GPa$^{-1}$ with $OF = 1.5300$.

On finishing GA optimisation, the coefficients $J_k$ were estimated once again by using the Levenberg–Marquardt local search method with fixed values for $\tau_k$ taking into account the region determined by GA (0.03, 0.04, 0.05 and 0.06 s). The convergence of creep coefficient $J_k$ values and the variation of the objective function value by using the LM method are shown in Figure 4. Optimal parameter values identified in LM runs are presented in Table 1. The optimal values for the viscoelastic parameters were $\tau_1 = 0.05$ s and $J_1 = 0.02250$ GPa$^{-1}$ corresponding to the best objective function value.

### Creep calibration for the leak case

In order to calibrate the system for the leak case, the transient solver was run considering the optimal values of coefficients $\tau_k$ and $J_k$ obtained for the non-leak case. The pressure wave propagation was assumed equal to 460 m/s and transient pressure data for the initial inflow of 1.84 L/s and leaking flow of 0.84 L/s at location P02 were used.

The effective leak area ($C_dA_0 = 3.814 \times 10^{-05}$ m$^2$) was determined using leak discharges and pressure heads
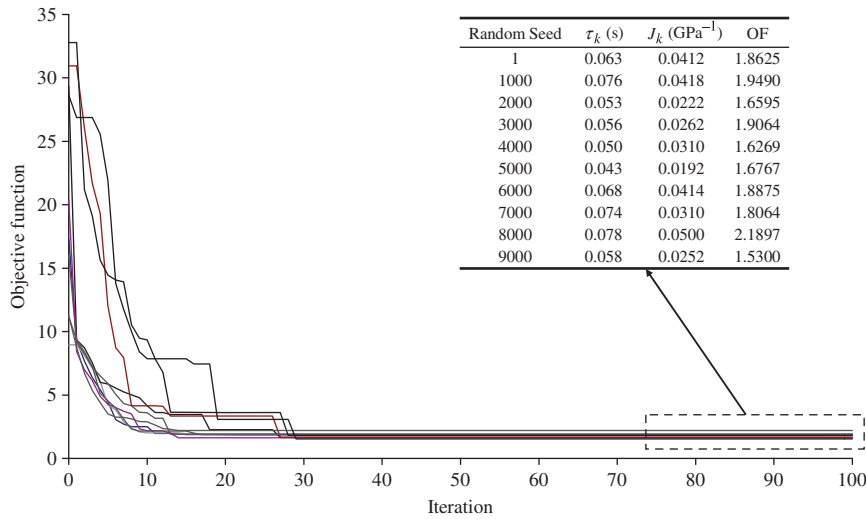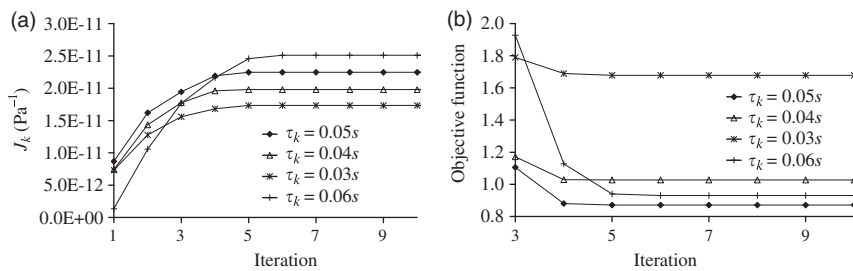
| Random Seed | $\tau_k$ (s) | $J_k$ (GPa$^{-1}$) | OF |
|---|---|---|---|
| 1 | 0.063 | 0.0412 | 1.8625 |
| 1000 | 0.076 | 0.0418 | 1.9490 |
| 2000 | 0.053 | 0.0222 | 1.6595 |
| 3000 | 0.056 | 0.0262 | 1.9064 |
| 4000 | 0.050 | 0.0310 | 1.6269 |
| 5000 | 0.043 | 0.0192 | 1.6767 |
| 6000 | 0.068 | 0.0414 | 1.8875 |
| 7000 | 0.074 | 0.0310 | 1.8064 |
| 8000 | 0.078 | 0.0500 | 2.1897 |
| 9000 | 0.058 | 0.0252 | 1.5300 |

**Figure 3** | Variation of the minimum objective function value (*OF*) for each GA simulation (10 random seeds) and the respective optimal values of the viscoelastic parameters ($\tau_1$ and $J_1$).



**Figure 4** | (a) Convergence of creep coefficients $J_k$ values and (b) variation of objective function value by using the LM method.

observed at location P02 for steady state flow (Figure 5 – $C_d A_0(2\ g)^{0.5} = 1.689 \times 10^{-04}$). The exponent was estimated at 0.5021, which is quite close to that in the orifice law, $Q = C_d A_0 (2g\Delta H)^{0.5}$. In this research work, the leak is not simulated by an orifice in the pipe wall but by means of a discharge pipe with an opened valve. The exponent of 0.5 is valid for orifices with constant section (not buried and with free discharge to the atmosphere) and this is the case as is

**Table 1** | Optimal parameter values identified in LM runs

| $\tau_1$ (s) | $J_1$ (GPa$^{-1}$) | *OF* |
|---|---|---|
| 0.03 | 0.0173 | 1.6781 |
| 0.04 | 0.0198 | 1.0271 |
| 0.05 | 0.0225 | 0.8712 |
| 0.06 | 0.0251 | 0.9304 |

proven in Figure 5, in which a power law with an exponent of pressure equal to 0.5 is determined.

Discrepancies between calculated and collected data gave rise to further investigation regarding the behaviour of other devices in the system. Due to the ball valve closure at the downstream end, the flow in the discharge line reduces rapidly but the pump keeps rotating in the normal direction. Moreover, because the check valve position is controlled by the flow and valve dynamics, a valve closure did not occur (the check valve opening was unchanged for the leak case) and the pump was still supplying the leak. This does not cause an instantaneous stoppage of the reverse flow with the corresponding pressure rise, as was observed in the non-leak case (Soares *et al.* 2008a, b). In this way, the check valve did not influence the numerical results obtained from the leak tests. The pressure wave due to the ball valve closure travels over the discharge line and, after reaching the pump,

**Figure 5** | Fitted relationship between leaking flow and pressure head at location P02.

$$Q_L = 1.689\text{E-}04\,(H_L - z_L)^{0.5021}$$

travels along the suction line in the direction of the tank. With regard to the pump characteristics, and for its complete mathematical representation, the suction pipe was not considered short (18 m) as compared to the discharge pipeline (67 m) and the propagation of transient pressures along the suction line was not neglected. Accordingly, the pump was described as a centrifugal pump with a long suction line, and another characteristic equation $C^+$ was included.

Additional numerical simulations were run to determine the parameters of the viscoelastic model for the leak case. Two different sets of parameters in the system were considered: (i) the first set was for the suction line and (ii) the second one was for the discharge line. This is because the pipe in the suction line was not rigidly fixed to the metal frame (unlike the discharge line) and, due to its arrangement outside of the laboratory, being exposed to high temperature variations.

Results from numerical simulations have shown that the creep coefficient for the suction line is 15–20 times larger than that for the discharge line. The high creep function obtained for the suction line is mainly due to both the displacement and the arrangement of the pipes. These effects are described by the high values of estimated creep parameters, which do not represent the actual rheological behaviour of the PVC material, but the combined mechanical behaviour of pipe material and pipe constraints. On the other hand, the creep function of the discharge pipe for the leak case was nearly the same as that obtained for the non-leak case.

Numerical results for transient pressures together with the observed data are presented in Figure 6 (inflow = 1.84 L/s; leak = 0.84 L/s) and Figure 7 (inflow = 2.47 L/s; leak = 0.73 L/s) for locations P06, P02, P01, P07 and P05. Numerical results obtained from the viscoelastic transient

solver fit extremely well with the collected pressure data which shows that the viscoelastic model can describe quite satisfactorily transient pressure wave attenuation and dispersion, as well as its shape.

## Creep determination by mechanical tests

The creep functions calibrated by the inverse model for the leak case and the non-leak case, as well as those obtained through mechanical creep tests carried out at various temperatures in the Department of Material Engineering of Instituto Superior Técnico, Lisbon, Portugal (Soares 2007), are shown in Figure 8.

A comparison between the creep functions determined by mechanical tests and by the inverse method for both non-leak and leak cases are quite consistent, indicating the calibration process to be valid. A small discrepancy between non-leak and leak cases could be a result of: (i) uncertainties in unsteady friction losses due to different inflow values (in the current system, unsteady friction effects are negligible when compared to pipe-wall viscoelasticity, and they were assumed to be described by the creep function), (ii) eventual temperature variations in the laboratory and (iii) the creep function can vary slightly in time due to the stress time history of the pipe, that is the number of transient tests carried out during a certain period of time. Successive transients that are carried out in the pipe tend to relax it. The time between transient tests is not sufficient for the complete recovery of the PVC pipe, as it does not have perfect linear viscoelastic behaviour as assumed in this study.

## LEAK DETECTION TESTS

The location of the leaks is based on the discretisation of the discharge line into several potential leak candidates close to the existing leak location. Results obtained for leak detection by using ITA in the EHC pipe system are presented in the following paragraphs.

During the experiments, the leak was located at node 72 (location P02). ITA was run using GA to locate this leak and its size for two steady state turbulent flows: Case A ($Q_0 = 1.84$ L/s, $Q_L = 0.84$ L/s) and Case B ($Q_0 = 2.47$ L/s,
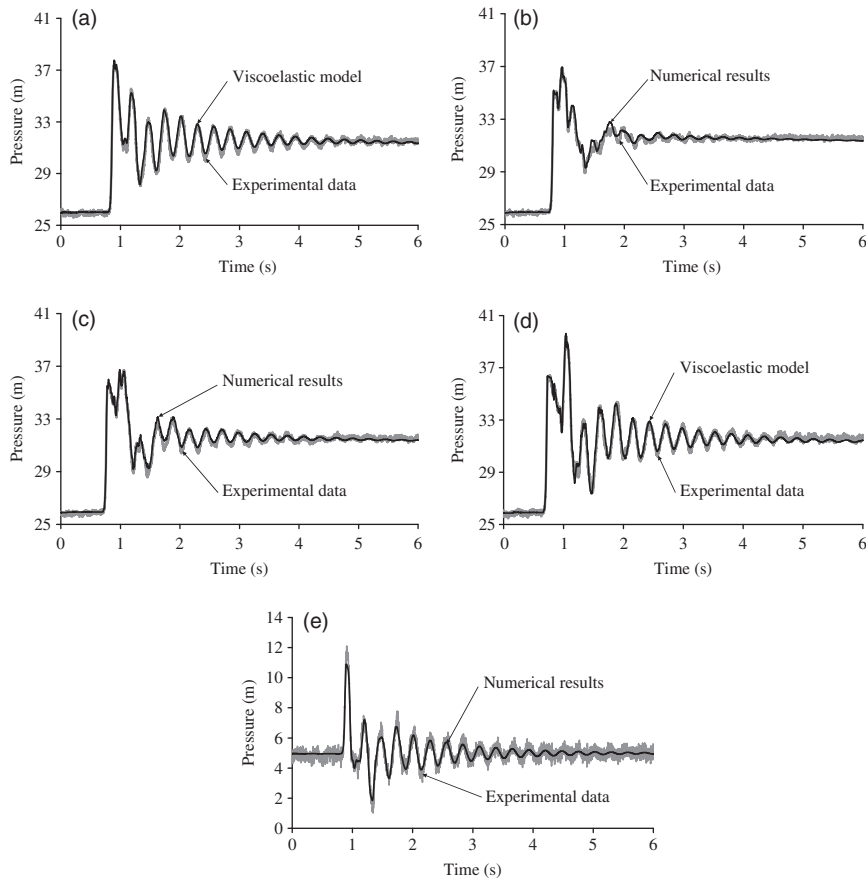
**Figure 6** | Numerical results of the viscoelastic transient solver versus transient pressure data for the leak test ($Q_0 = 1.84$ L/s; $Q_L = 0.84$ L/s) at different locations (distance from the pump section): (a) P06 (7.20 m), (b) P02 (32.40 m), (c) P01 (46.10 m), (d) P07 (67.00 m) and (e) P05 (-0.20 m).

$Q_L = 0.73$ L/s). With regard to the high leak flows, other tests with lower leaks have been carried out, but the leak reflection had the same amplitude as the reflections observed due to other features – the experimental set-up is quite complex with several branches, valves, changes of pipe diameters, etc, with several uncertainties associated with the pressure transients collected in the system (Soares *et al.* 2008b). Thus, the application of ITA for this pipe system was more successful for high leak flows, which leads to the state that the major potential of the technique presented in this paper is for the detection of large bursts or opened pipe branches in complex water transmission mains that cannot be detected by other techniques.

In this study, the application of ITA is based on a multi-step procedure, as presented in Figure 9. In the first step (Step I – Figure 9(a)), the discharge line ($L = 67.30$ m) was divided into seven sections. Seven equally spaced nodes ($\sim 9.60$ m) were assumed as potential candidates for leak locations. In

order to reduce uncertainties in the search, ITA was run using ten distinct initial populations of solutions (GA random seeds) for each step. In Step II (Figure 9(b)), ITA was applied for another set of seven potential leak locations (spaced $\sim 5$ m) covering $\sim 30$ m around the main leak location obtained in Step I. In the last step (Step III – Figure 9(c)), a set of seven equally spaced nodes (2.70 m) were assumed as potential candidates for leak locations covering 16.20 m near the leak detected in Step II. In this way, the assumption is to leave the model calculating the discharge flow at several nodes simultaneously, refining the nodes close to all the leaking ones. The leak is determined by the comparison between collected data at location P07 and the numerical results calculated by using a previously calibrated hydraulic transient solver. The pressure damping was not directly used for leak detection, and the leak reflection can hardly be seen in the transient pressure trace because of the multiple reflections that occur in the system (Soares *et al.* 2008b). The
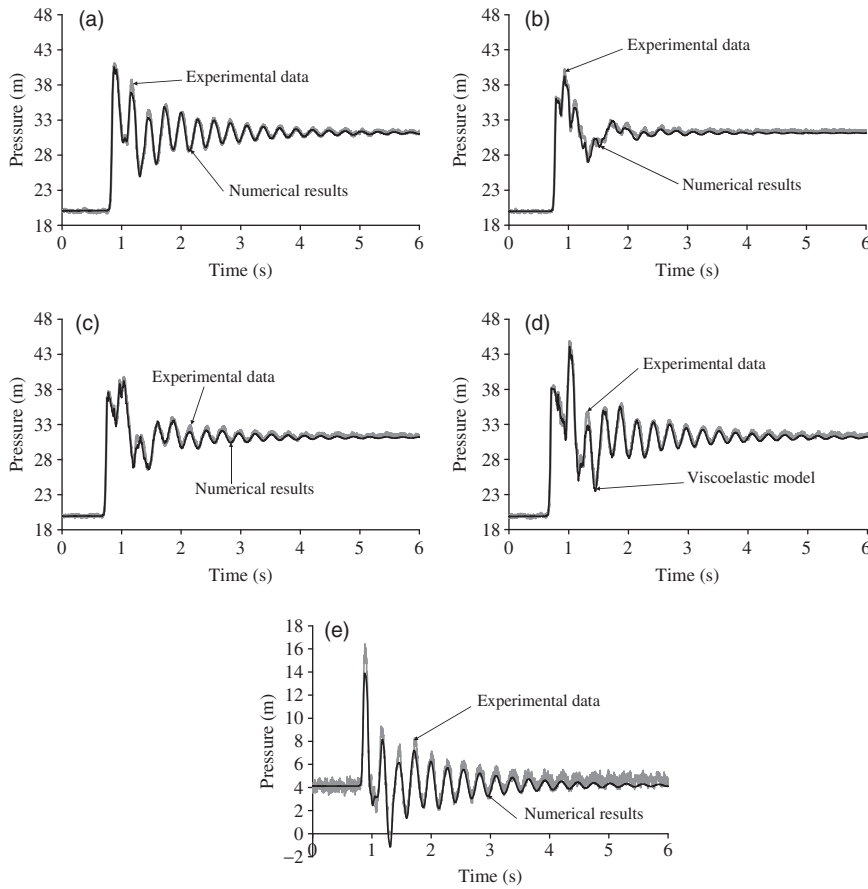
**Figure 7** | Numerical results of the viscoelastic transient solver versus transient pressure data for the leak test ($Q_0 = 2.47$ L/s; $Q_L = 0.73$ L/s) at different locations (distance from the pump section): (a) P06 (7.20 m), (b) P02 (32.40 m), (c) P01 (46.10 m), (d) P07 (67.00 m) and (e) P05 (-0.20 m).

pressure signal collected at location P07 has been used in the optimisation process because the transient event was generated by the ball valve closure located immediately downstream from the pressure transducer. This can reveal information



**Figure 8** | Creep function determined by experimental tests versus calibrated creep function for PVC pipes (non-leak and leak cases).

concerning the several pressure wave reflections along the pipeline, facilitating the case of practical investigations. Transient pressures collected at P01, P02, P05 and P06 were not used in the leak detection and calibration procedures. This is an advantage of transient analysis, which does not require pressure observations at several points of the system.

Optimal leak locations obtained by using ITA are presented in Figure 10 in terms of both frequency of GA detection (for 10 GA random seeds) and minimum value of objective function for each step. Optimal $C_d A_0$ (effective leak areas) values for the minimum objective function value identified in GA leak detection runs are shown in Table 2. The accuracy of the effective leak area ($C_d A_0$) value obtained by GA simulations for the actual leak location (location P02) is depicted in Table 3. Calculated pressures for the optimal leak location at each step are presented in Figure 11 for location P07.
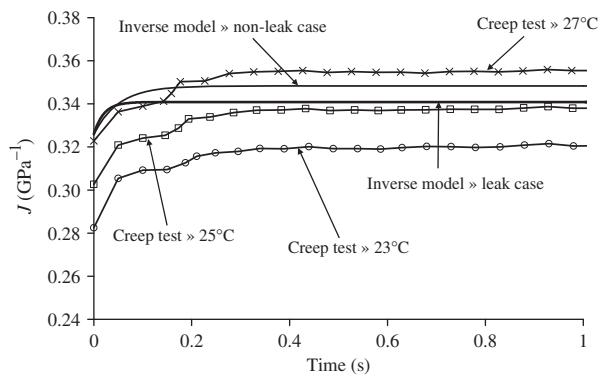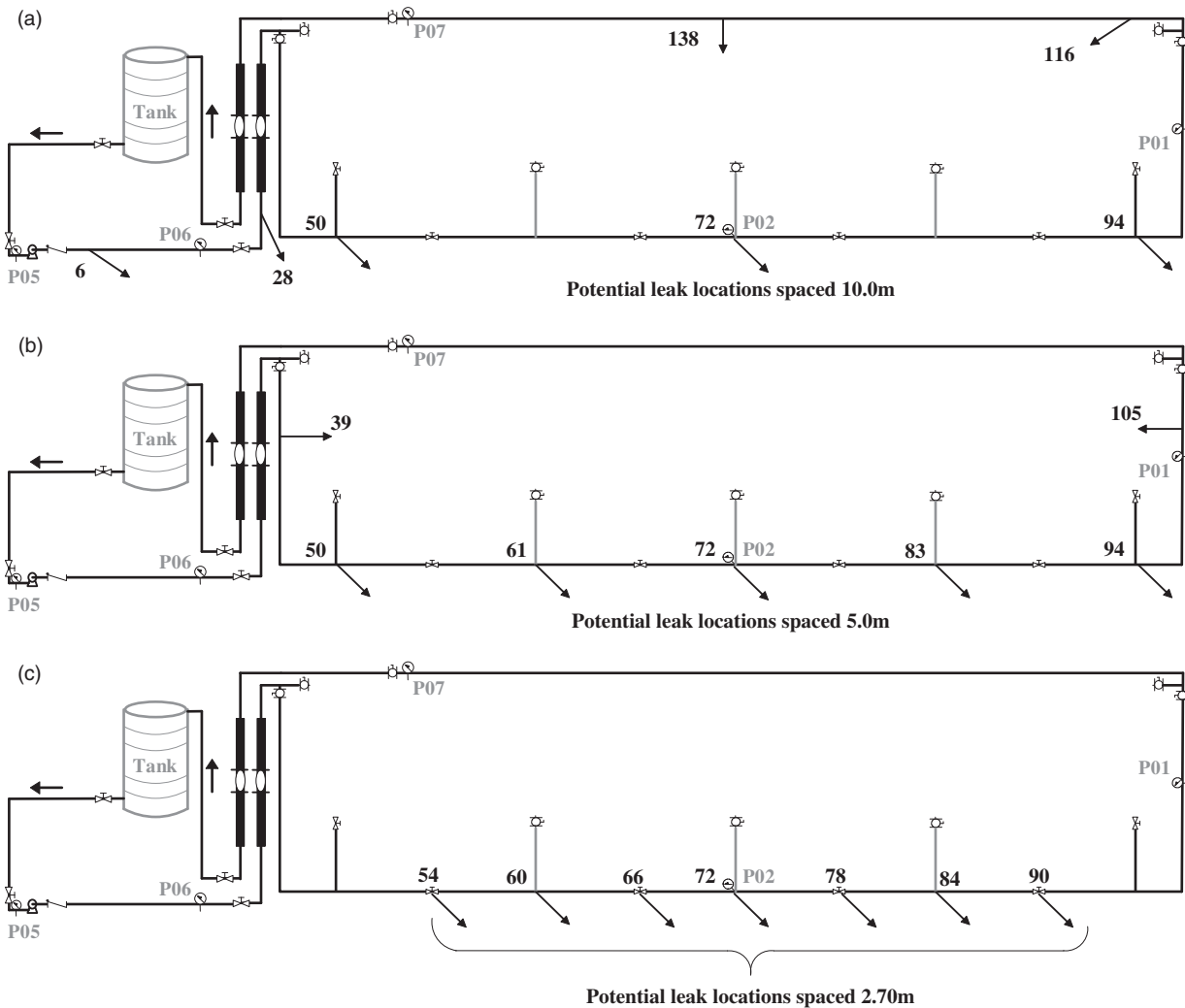
**Figure 9** | Multi-step procedure for leak detection for different potential leak locations equally spaced in the suspected reach: (a) 10 m, (b) 5.0 m and (c) 2.70 m.

In this study, the residuals (errors) in the LSE method were not discussed, since the aim of this paper is to present the application of the technique and not to extensively analyse the numerical problems behind the optimisation procedure. The major difficulty of the application of the technique is the simultaneous calibration of the hydraulic model with leak detection. The problem with the additional analysis of parameter uncertainty is that the main uncertainties in the leak detection problem (by ITA) are not due to the better- or worse-posed problem in terms of optimisation, but due to the hydraulic transient solver being capable of well-describing multiple features and the dynamic behaviour of the system. In this paper, the PVC rheological behaviour calibration as well as the multiple complex features modelling of the

system (boundary and internal conditions) required extensive study before the application of the leak detection technique. In order to improve results, an uncertainty estimation method could be coupled to the inverse model (Van Griensven & Meixner 2007).

The leak location is properly identified in Case B for all three refinement steps of the ITA. The same does not occur in Case A, in which the ITA indicates a leak zone (2.70 m length) near the actual leak location as the candidate leak nodes along the pipe are refined. A similar case study is reported by Covas (2003) when testing ITA with the Levenberg–Marquardt algorithm: for higher refinements of leak candidate nodes, the optimisation method cannot locate the leak and spreads leaks with a normal-like distribution around the
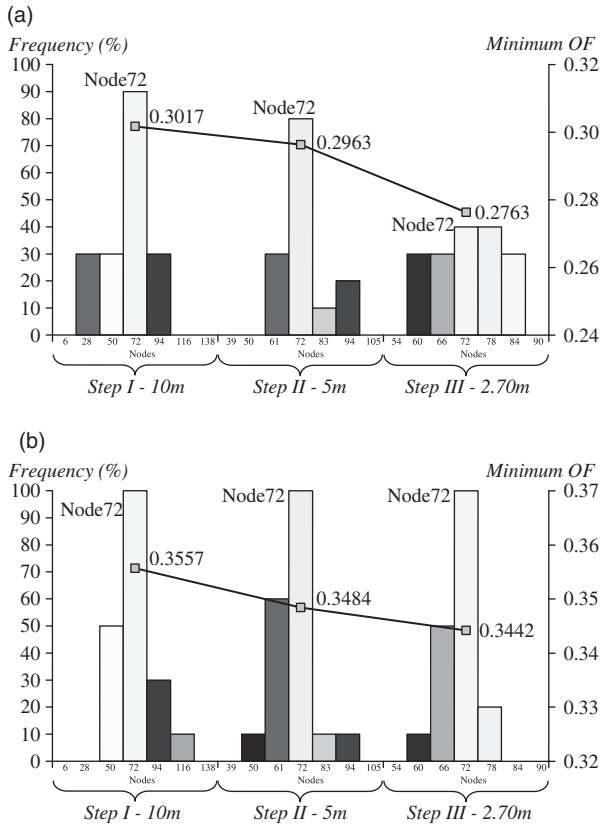
(a)



(b)



**Figure 10** | Optimal leak locations obtained by ITA for: (a) Case A and (b) Case B.

actual leak location. Moreover, when the leak is not exactly located at a leak node, the effective leak area is divided between the two nodes that are closest to the leak location. In practice, the leak is not exactly located, but the model can give the region of the pipeline (up to 4% of the total length in this work) in which a leak is occurring.

In this research work, leaks can be located with an accuracy corresponding to 4% ($\Delta x/L = 2.70/67.30$) of the total length of the discharge line, despite measurement errors (noise in the pressure signal), errors in calibrated viscoelastic parameters of the hydraulic transient solver and the optimisation method capability of determining the best solutions. Accordingly, leaks can be quantified with 62–90% accuracy in Case A and with 84–93% accuracy in Case B.

## CONCLUSIONS

The current paper presented the application and testing of Inverse Transient Analysis (ITA) using physical data collected from an experimental facility composed of polyvinyl chloride pipes (PVC). A hydraulic transient solver that takes into account the viscoelastic mechanical behaviour of plastic pipes was presented and used for leak detection.

The creep function was determined by using both ITA (for non-leak and leak cases) and creep tests with PVC

**Table 2** | Optimal $C_dA_0$ values identified in GA leak detection runs

| | Nodes and the respective calculated and true $C_dA_0$ values (m²) | | | | | | | OF |
|---|---|---|---|---|---|---|---|---|
| *Step I* | **6** | **28** | **50** | **72** | **94** | **116** | **138** | |
| Case A | 0.0 | 2.427E-07 | 7.425E-06 | 3.423E-05 | 0.0 | 0.0 | 0.0 | 0.3017 |
| Case B | 0.0 | 0.0 | 0.0 | 4.427E-05 | 0.0 | 0.0 | 0.0 | 0.3557 |
| True value | 0.0 | 0.0 | 0.0 | 3.814E-05 | 0.0 | 0.0 | 0.0 | |
| *Step II* | **39** | **50** | **61** | **72** | **83** | **94** | **105** | |
| Case A | 0.0 | 0.0 | 0.0 | 4.239E-05 | 0.0 | 0.0 | 0.0 | 0.2963 |
| Case B | 0.0 | 0.0 | 4.243E-06 | 3.494E-05 | 2.148E-06 | 0.0 | 0.0 | 0.3484 |
| True value | 0.0 | 0.0 | 0.0 | 3.814E-05 | 0.0 | 0.0 | 0.0 | |
| *Step III* | **54** | **60** | **66** | **72** | **78** | **84** | **90** | |
| Case A | 0.0 | 0.0 | 1.972E-05 | 2.364E-05 | 0.0 | 0.0 | 0.0 | 0.2763 |
| Case B | 0.0 | 0.0 | 0.0 | 4.090E-05 | 0.0 | 0.0 | 0.0 | 0.3442 |
| True value | 0.0 | 0.0 | 0.0 | 3.814E-05 | 0.0 | 0.0 | 0.0 | |

**Table 3** | Accuracy of leak $C_dA_0$ value obtained by GA leak detection runs

|  |  | Calculated $C_dA_0$ (m²) | True $C_dA_0$ (m²) | Error (%) | Accuracy (%) |
|---|---|---|---|---|---|
| Case A | *Step I* | 3.423E-05 | 3.814E-05 | 10.3 | 89.7 |
|  | *Step II* | 4.239E-05 | 3.814E-05 | 11.1 | 88.9 |
|  | *Step III* | 2.364E-05 | 3.814E-05 | 38.0 | 62.0 |
| Case B | *Step I* | 4.427E-05 | 3.814E-05 | 16.1 | 83.9 |
|  | *Step II* | 3.494E-05 | 3.814E-05 | 8.4 | 91.6 |
|  | *Step III* | 4.090E-05 | 3.814E-05 | 7.2 | 92.8 |
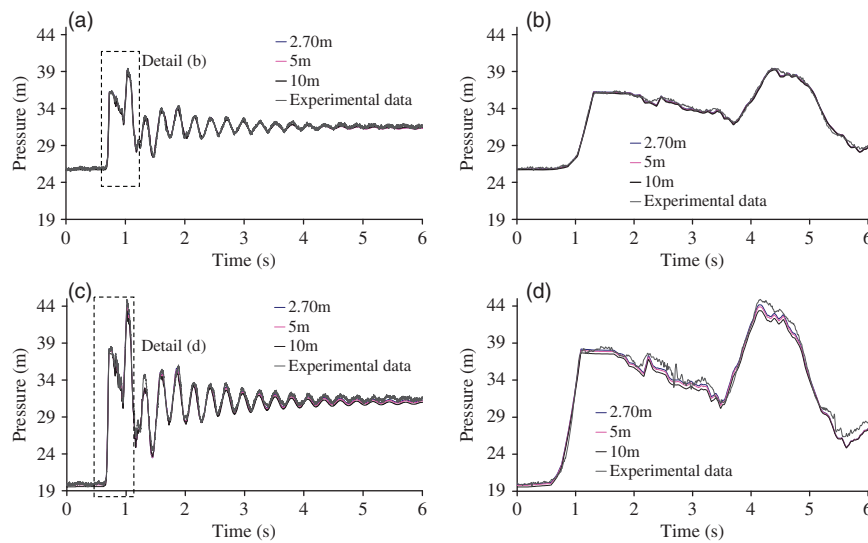


**Figure 11** | Calculated pressure heads for optimal leak location versus experimental data for: (a) Case A, (b) detail of first pressure peak for Case A, (c) Case B and (d) detail of first pressure peak for Case B.

specimens. Calibrated creep functions fitted very well with the creep function determined by creep tests. It is shown that the numerical results for pressure variation obtained by using the viscoelastic model can describe transient pressure wave attenuation, dispersion and shape.

The application of ITA to leak location was based on a multi-step procedure carried out by a GA search method. Results have shown that leaks can be accurately located with a 4% uncertainty in a 67 m long pipe system (depending on the discretisation of the system model). The use of a hybrid optimisation method with a global–local search method could significantly improve the leak detection procedure in terms of convergence speed and accuracy.

In this research work, parameters of the viscoelastic transient solver were determined before the leak detection simulations. However, given the soundness of the creep functions obtained through calibration, creep calibration and leak detection can be carried out simultaneously when applying ITA to prototype systems.

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