Direct backward transient analysis for leak detection in pressurized pipelines: from theory to real application

Ali Haghighi, Didia Covas and Helena Ramos

ABSTRACT

A novel transient-based technique – the direct backward transient analysis (DBTA) – for leak location of single pressurized pipes is presented and tested using real-life data. A transient flow is generated in the pipe by closing the downstream end valve. The transient pressure signal is then measured only at the valve location. Using the method of characteristics and exploiting the measurements after full valve closure, the transient flow is backwardly analyzed by sweeping the pipe from the downstream to the upstream end. Knowing the upstream end heads, additional equations are developed to make the problem of leak detection determined and possible to be solved directly. A system of equations and unknown variables of leaks and flow specifications are then established and simultaneously solved together. Eventually, nodes with non-zero leak size are introduced as leaks. Finally, the method is applied to a real transmission pipeline, Lintrathen East Trunk Main Network at Scottish Water (Dundee, UK) and its abilities are investigated. The results show that the method is capable of dealing with real systems and is reliable, fast and easy to use.

Key words | backward transient analysis, direct leak detection, method of characteristics

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NOTATION

A	Cross-sectional area of pipe
a	Wave speed
Ae	Effective leak area
A_L	Apparent leak area
C	Objective function
C_d	Coefficient of discharge
CN	Courant number
D	Diameter of pipe
f	Darcy–Weisbach friction factor
f_q	Quasi-steady friction factor
fr_s	Sampling frequency
g	Gravitational acceleration
H	Piezometric head
K	Number of calculated reservoir head
k	Brunone's decay coefficient
L	Length of pipe
m	Number of leaks
n	Number of characteristic nodes
Q	Instantaneous pipe discharge
q	Leak discharge
t	Time
T_c	Valve closure time
T_s	Time duration of transient sampling
T_{th}	Theoretical period
C^*	Vardy and Brown's shear decay coefficient
x	Distance along pipe
z	Elevation of leak location
φ	BTA function
Δt	Time step
Δx	Change in distance

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INTRODUCTION

Nowadays, leaks and their economic and environmental costs are well-known problems. Many studies around the world report huge losses of drink water due to leaks in pipelines (AWWA 1990; Jowitt & Xu 1990; Weil 1993). As a consequence, many efforts and investigations are still highly demanded to develop and promote leak detection methods. In recent years, several model-based methods for leak detection have been introduced, which can be categorized into two different approaches – time and frequency domain analyses. Most time domain approaches are in the subcategory of inverse transient analysis (ITA) (Liggett & Chen 1994; Vitkovsky *et al.* 2000b, 2007; Kapelan *et al.* 2003; Covas *et al.* 2005a, b; Khomairi 2008; Shamloo & Haghighi 2009, 2010, 2011). ITA is a well-known approach for leak detection and calibration of pressurized pipe systems. These methods initiate by: (1) generating a transient state in the pipe by closing a valve; then (2) transient flow characteristics (mostly pressures) are measured at any location of the system, preferably close to the site where the transient is initiated; afterwards, (3) pipe and the transient conditions are numerically modeled by a hydraulic transient solver. This model is very important to the ITA success in which all pipe features, boundary and initial conditions should be accurately described. After that, (4) based on measurements and on the numerical model, an optimization problem is defined with a least squares criterion objective function. This problem is to minimize the differences between the measured and calculated pressures or flows. In this programming, leak parameters in the pipe including the number, size and location of leaks are considered as decision variables. Finally, (5) an optimization algorithm is used to solve the problem.

These steps configure the main structure of ITA-based methods but there are definitely a lot of details and also several uncertainties associated to each individual step. The current work aims to overcome some of the main uncertainties of ITA by introducing a novel time-domain approach for leak detection in pressurized pipes. The model is independent of the accurate knowledge of valve specifications, initial boundary conditions and also has no need for lengthy transient measurements and simulations. In this method, the mentioned steps for ITA are significantly simplified, and many uncertainty resources in modeling are removed. The new method, referred to as backward transient analysis (BTA), is based on measurements and hydraulic numerical methods. Using BTA, the whole pipe length is backwardly analyzed and leaks are detected from the downstream to the upstream end for only one theoretical wave period of the transient flow. The method is independent of the valve type, the valve maneuver and the closure time and does not require posing initial conditions. In what follows, the main principles of the proposed method are described step-by-step and a real-life pipeline is taken into account for leak location.

GOVERNING EQUATIONS

For most transient hydraulic applications, the governing equations based on the continuity and momentum principles are (Chaudhry 1987):

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

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0 \tag{2}$$

where x = distance along pipe, t = time, a = wave speed, g = gravitational acceleration, A = pipe cross-sectional area, D = pipe diameter, Q = instantaneous discharge, H = instantaneous piezometric head, and f = friction factor which can be described by steady, quasi-steady or unsteady state conditions. These equations are typically solved by using the method of characteristics (MOC), although other numerical methods may be used (e.g. finite differences and finite volume method).

For unsteady flow, the energy losses due to fluid viscosity are important and their approximation by a quasi-steady approach in compatibility equations includes uncertainties (Wylie & Streeter 1993). Steady or quasi-steady assumption of friction losses is satisfactory for slow transients where the wall shear stress has a quasi-steady behaviur (Bergant *et al.* 2001); however, is considerably imprecise for fast transient events. Unsteady friction effects are considered herein by using Brunone's model (Brunone *et al.* 1991, 1995) which has been modified by Vitkovsky *et al.* (2000a), described by the following equation:

$$f = f_q + \frac{kDA}{Q|Q|}\left(\frac{\partial Q}{\partial t} + \text{asign}(Q)\frac{\partial Q}{\partial x}\right) \tag{3}$$

where f_q=quasi-steady friction factor from the Colebrook–White formula, $\text{sign}(Q) = \{+1 \text{ if } Q \geq 0 \text{ and } -1 \text{ if } Q < 0\}$ and

k = Brunone's decay coefficient that can be predicted either empiricaly or analytically using Vardy and Brown's shear decay coefficient C^* as follows:

$$k = \frac{\sqrt{C^*}}{2} \quad (4)$$

where $C^* = 0.0476$ for laminar flows and $C^* = 7.41/\mathrm{Re}^{\log(14.3/\mathrm{Re}^{0.05})}$ for turbulent flows, and Re = instantaneous Reynolds number. Brunone's model has been found as one of the easiest to be implemented and has better results in modeling unsteady friction effects. It has been validated through many experimental works (Bergant *et al.* 2001; Ramos *et al.* 2004). Nevertheless, uncertainties due to the estimation of Brunone's and also quasi-steady coefficients can still be significant, especially in rapid transients which are very important for leak detection purposes.

A finite difference scheme will be used to numerically approximate unsteady friction factor by Equation (3) at each time step. Furthermore, in particular cases, other equations associated with unsteady friction losses, the rheological behavior of the pipe (e.g. viscoelastic), fluid-structure interaction and other dynamic effects may be considered too.

The principle of most model-based leak detection methods is to change decision variables in order to match the calculated transient pressures with the collected pressures. Accordingly, the numerical modeling should be very precise in the simulation of the transient pipe flow. Besides, there are several uncertainties and undetermined parameters which influence the model reliability, such as the valve maneuver, unsteady friction losses, initial steady state conditions and collected transient data. Among these, the valve as the transient initiator plays a significant role in the whole leak detection process.

To generate a transient event in a pipe, the type of valve, the closure time and the maneuver not only affect the effectiveness of the transient event on leak detection, but are also very important to the numerical model for which the valve maneuver should be precisely simulated. This importance is more serious in case of real-life pipes generally with old worn-out valves. In these systems, the valve should be closed with a slow maneuver to prevent the occurrence of undesirable waterhammer waves and the numerical simulation of the valve operation during its closure is a huge uncertainty to the numerical model. These may cause serious concerns on the application of inverse transient analysis and, consequently, the reliability of any leak detection and calibration method requiring the numerical valve modeling. Therefore, omitting the valve simulation for transient numerical modeling is a main target of the proposed method.

BACKWARD TRANSIENT ANALYSIS

Considering the referred issues and focusing on solutions to reduce those uncertainties, BTA is now developed. The logic of the method will be presented for a system without leakage and then it will be further explained and developed for leak detection.

A simple pipe is considered without leakage, as shown in Figure 1. By closing the downstream end valve, a transient event is induced in the system and transient pressures are measured at the downstream end (i.e. at valve location).

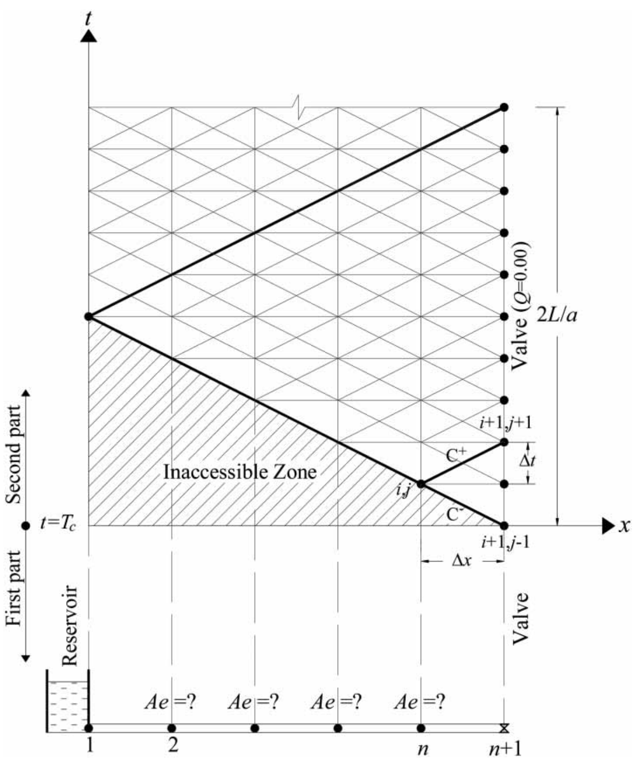

Figure 1 | Backward characteristics grid.

For this situation, the induced transient event can be divided into two distinct parts:

1. The first part is during the valve closure (when $t < T_c$) and,
2. The second part is after the full valve closure (when $t \geq T_c$, where T_c is the valve closure time).

In the first part (i.e. while the valve is being closed), the flow at the valve decreases from initial flow to zero. The pattern of this variation is dependent on the valve type and maneuver. Numerical modeling of valve maneuver requires simplifying assumptions which may lead to significant uncertainties in real-life applications as discussed.

In the second part (i.e. after the valve is fully closed), the flow at the valve location is obviously equal to zero, and the valve behavior can be described as a dead-end. Undesirable issues associated to the valve simulation and to the initial valve position are avoided when collecting data after the full valve closure. Accordingly, the boundary conditions at the downstream end are perfectly known, since instantaneous pressures are measured and the discharge is null. Based on these boundary values of pressure and flow and considering the pipe wave speed, a regular staggered mesh can be defined for flow analysis in time-space domains in which the courant number $CN = a\Delta t/\Delta x$ is considered equal to unit (Figure 1).

In a system without leakage, there are two unknown variables at each node, which are the instantaneous head and the discharge. Accordingly, to calculate these variables, two equations based on governing Equations (1) and (2) are needed for each node. MOC is the most popular technique to analyze transient state in pipe systems. However, the traditional scheme of MOC cannot be applied herein since initial conditions and valve description have been omitted from the modeling. For this purpose, a new scheme of MOC introduced by Shamloo & Haghighi (2009) is applied to backwardly describe the transient state equations. Simply speaking, equations of continuity and momentum are linearly combined and the resulting ordinary differential equations are integrated along new semi-implicit positive line PC and explicit negative line PA as depicted in Figure 1. The final equations are obtained as following:

$$Q_{i,j} - Q_{i+1,j+1} + \frac{gA}{a}(H_{i,j} - H_{i+1,j+1}) - RQ_{i,j}|Q_{i+1,j+1}|\Delta t = 0 \quad (5)$$

$$Q_{i,j} - Q_{i+1,j-1} - \frac{gA}{a}(H_{i,j} - H_{i+1,j-1}) + RQ_{i,j}|Q_{i+1,j-1}|\Delta t = 0 \quad (6)$$

where $Q_{i,j}$ and $H_{i,j}$ are instantaneous discharges and piezometric heads at points respectively at node i time step j. Considering Equation (3), $R = f/2DA$ comprises of two quasi-steady and unsteady parts. This equation is also approximated by a simple finite difference scheme and added to the above governing equations. Equations (5) and (6) are respectively valid along the positive and negative characteristic lines C^+ and C^-.

Using the proposed scheme with Equations (5) and (6), the transient flow conditions are calculated along the t-axis for each node (from downstream) and then along the x-axis for all nodes backwardly (i.e. domains of time and space are analyzed, respectively). Consequently, the time histories of transient flow features at all characteristic nodes are calculated by backward swiping of the pipe from the known downstream boundary condition to the upstream end. Assuming T_s as the duration of pressure sampling at the valve, the number of K upstream values can be calculated as:

$$K = \frac{T_s - 2L/a}{\Delta t} \quad (7)$$

where Δt=time step. As presented in Figure 1, there is an 'inaccessible zone' indicated with the hatched area in the characteristics grid. The reason of appearance of this zone is related to the new C^+ equations applied in the BTA. As seen in Figure 1, when the calculations are started from the downstream end, the characteristic equations, explicit C^- and semi-implicit C^+, both connect the current node i at time j to its right side neighbor node $i+1$ at times $j-1$ and $j+1$, respectively. This scheme is different with the conventional MOC that relates node i to its right and left nodes ($i+1$ and $i-1$) at time $j-1$. When the described scheme of BTA is moved to the upstream end, a triangle area appears in the characteristics grid in which the flow specifications cannot be calculated. This is why this area is called the inaccessible zone. Fortunately, the initial pipe conditions are located in this zone. Therefore, there is no need to impose the initial conditions in the numerical modeling as well as the valve features simulation. There is no need to define upstream boundary conditions since they are automatically calculated by the model. So, not only some major modeling difficulties are removed when using BTA, but also significant uncertainty sources are totally avoided. Furthermore, in this method, calculations can be started at any time after valve closure, in which noise in the measured signal has disappeared. Consequently, BTA is very easy and fast to implement and would be more reliable than traditional MOC to be applied for leak detection purposes. This aim is dealt with in the next section.

LEAK DETECTION METHODOLOGY

Leak detection methods aim to find the leak parameters, such as the number of leaks, their locations and sizes. These unknown parameters are added to the transient flow specifications, being head and discharge at characteristic nodes. In this condition, the number of unknown variables is more than the known equations. This is why the problem of leak detection is underdetermined and optimization tools are often needed to be applied in the context of inverse problems. In addition to the inverse solutions, this work also aims to present an alternative approach, which makes the problem of leak detection determined and easier to be solved independently of optimization methods and their relative problems.

Leak simulation

Leak effects in a pipe depend on the orifice shape, transient characteristics, leak location and groundwater level for buried pipes. The leak discharge is expressed by the orifice equation as follows:

$$q_{i,j} = \mathrm{Ae}_i\sqrt{2g(H_{i,j} - z_i)} \tag{8}$$

where $\mathrm{Ae}_i = (C_\mathrm{d}A_\mathrm{L})_i$ effective leak area, C_d = coefficient of discharge, A_L = leak area, z_i is elevation at node i and $q_{i,j}$ is the instantaneous leak discharge at the leak location i at time step j. Flow at a leaky node is divided into two parts of left and right side discharges (Figure 2) which are related to each other with the leak and continuity equation as follows:

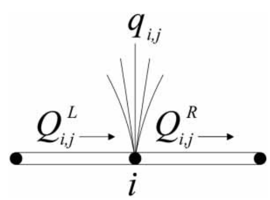

Figure 2 | A leaky node.

$$Q^\mathrm{L}_{i,j} = q_{i,j} + Q^\mathrm{R}_{i,j} \tag{9}$$

in which $Q^\mathrm{L}_{i,j}$ and $Q^\mathrm{R}_{i,j}$ are instantaneous discharges in left and right sides of node i respectively. Equation (9), along with the defined positive and negative characteristic Equations (5) and (6), is developed at leaky nodes.

DEVELOPMENT OF BTA FOR LEAK DETECTION

The BTA method, as described earlier, includes remarkable advantages for leak detection of real-life pipes. On this basis, BTA is developed to introduce a new leak detection method in which leaks are directly detected as well as flow characteristics being determined along the pipe length.

Not knowing the number of leaks and their locations, all characteristic nodes are assumed as potential leak locations with unknown effective leak areas (Figure 1). With this assumption, another unknown variable of effective leak area Ae is added to unknown flow specifications of head and discharge at each candidate node; however, the difference is that Ae is considered to be constant at each node along the time axis.

As shown before, BTA directly uses measurements at the downstream end for backwardly analyzing the pipe. Using this method for pipes without leaks, the upstream boundary conditions are basically not required to be defined. In fact, they are automatically calculated through the backward analysis. In the absence of leaks, BTA is a determined problem that is totally independent of the upstream boundary conditions. Consequently, the observed and calculated flow characteristics at the upstream boundary would be the same. However, for a system with leaks, the process of BTA cannot be explicitly moved from downstream to upstream since there are unknown discontinuities of leaks at characteristics nodes. In this condition, using BTA, all flow characteristics at each node along the pipe are obtained as function of leak areas after that node to the downstream (Figure 1). Parametrically developing of BTA equations along the pipe, for instance if all the characteristics nodes are considered to be potential leak candidates, piezometric heads are obtained as follows for each half period of analysis:

$$\begin{aligned} &H_{n-1,j+1} = \varphi(\mathrm{Ae}_n) \\ &H_{n-2,j+2} = \varphi(\mathrm{Ae}_n, \mathrm{Ae}_{n-1}) \\ &\cdot\cdot \\ &\cdot\cdot\cdot\cdot \\ &H_{1,j+n-1} = \varphi(\mathrm{Ae}_n, \mathrm{Ae}_{n-1}, \ldots, \mathrm{Ae}_2) \end{aligned} \tag{10}$$

in which φ is actually the function of BTA including measured data, compatibility equations of continuity, momentum, unsteady friction losses and leak continuity equation written in the proposed format as described above under BTA. It is worth noting that in Equation (10), point (i,j) at node n in Figure 1 has been considered as the reference point. Accordingly, the piezometric heads at the upstream end are affected by all the leak areas along the pipe and are calculated as a function of them. The comparison between the calculated upstream heads (for a certain assigned leak areas) and the actual observed values is the key point to judge the results and to solve the problem. On this basis, two approaches are introduced in the following paragraphs: *direct solution* in which leak areas are directly calculated through the transient analysis as well as flow characteristics, and *inverse solution* which is based on the definition of an inverse problem to be solved by an optimization solver.

Direct solution

When applying BTA for leak detection, the number of leaks, m, with unknown sizes is initially assumed at characteristics nodes where $m \leq n-1$ (except those at the upstream and the downstream ends). Equations of BTA are parametrically developed to the upstream end as a function of leak areas. In this condition, the problem of leak detection is underdetermined with m degrees of indeterminacy. Therefore, m additional equations are required to solve the problem. These equations could be obtained from the observed upstream heads. Through the BTA, as illustrated in Figure 3, using each half period ($2L/a$) of measured data at the downstream end, one head at the upstream end (e.g. at the reservoir) can be achieved along time (see triangle ABC in Figure 3). By backward analysis of a period ($4L/a$) of measurements, the number of $n+1$ upstream heads are obtained as a function of leak areas. These relevant functions should be equal to the corresponding observed values at the upstream end. This fact gives the m necessary equations. On this basis, the number of m equations is considered from the upstream end as follows:

$$\begin{aligned} &\varphi_1(\mathrm{Ae}_1, \mathrm{Ae}_2, \ldots, \mathrm{Ae}_m) - H'_{1,j} = 0 \\ &\varphi_2(\mathrm{Ae}_1, \mathrm{Ae}_2, \ldots, \mathrm{Ae}_m) - H'_{1,j+1} = 0 \\ &\cdot\cdot \\ &\cdot\cdot\cdot \\ &\varphi_m(\mathrm{Ae}_1, \mathrm{Ae}_2, \ldots, \mathrm{Ae}_m) - H'_{1,j+m-1} = 0 \end{aligned} \tag{11}$$

in which $H'_{1,j}$ is observed as the piezometric head at the upstream boundary (node 1) at time step j and functions named φ_r (where $r = 1$ to m) are different in usage of measured data from the downstream end (e.g. φ_1 uses measured pressures at the valve location from $j = 1$ to $2n+1$ and φ_2 uses the data from $j = 2$ to $2n+2$ and so). On the other hand, each φ_r reflects a certain series of the

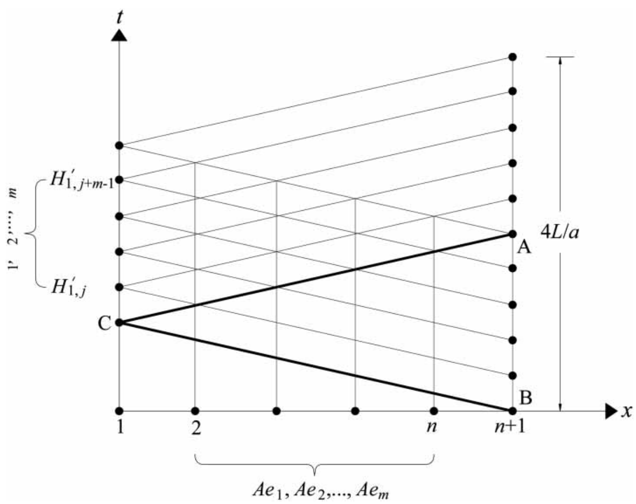

Figure 3 | System of unknown variables and equations.

measured data at the downstream. For this purpose, a numerical model is developed to evaluate φ functions as function of leak areas based on the governing equations.

Eventually, a system of unknowns and equations is achieved which makes the problem of leak detection determined and directly solvable. Because of terms of leak effects in φ equations, they are non-linear and could be solved by numerical methods such as Newton–Raphson (which has been used herein) or alternatively applying optimization solvers. Using only one period of measurement, the pipe is entirely swept for leak detection as well as flow characteristics being analyzed.

The proposed scheme is very fast with a small volume of calculations. This method can be easily repeated using other periods of measurements. This is a remarkable advantage of the method that lets the reliability of the results to be analyzed using only one transient test with a few numbers of periods. Generally, the period of solution is totally dependent on the user and can be considered from everywhere in the measured signal. This period has an effective role in the success of applied leak detection.

Inverse solution

Knowing the upstream boundary conditions, an alternative way to solve the problem is defining a non-linear programming (NLP) problem and solving it inversely. Thus, an objective function with the least squares criterion is defined to minimize differences between measured and calculated pressure heads at the upstream end:

$$C = \sum_{j=S}^{K} (H_{1,j} - H'_{1,j})^2 \tag{12}$$

in which C is the objective function, S is the time step of the first accessible upstream head after valve closure, K is the final time step considered for inverse solution (Equation 4), and $H_{1,j}$ and $H'_{1,j}$ are respectively the calculated and observed pressure heads at the upstream end.

In the inverse solution, the BTA is designed as an optimization problem in which the leak areas at characteristics nodes are its decision variables. Herein, the objective function is minimized with respect to the leak areas by the method of sequential quadratic programming (SQP) using MATLAB. SQP has been already applied in previous works (Shamloo & Haghighi 2009, 2010) and was found to be a powerful tool to deal with leak detection problems. SQP is a gradient-based method involving major and minor iterations. At each major iteration a quadratic programming (QP) subsystem is used to generate a search direction toward the next iteration. Solution of the QP subsystem is itself an iterative procedure (Barcelay 1999).

Eventually, using each of the direct or inverse solution ways, a quantity is assigned to each leak candidate. Nodes with non-zero leak areas are reported as leaks and ultimately the number, location and size of leaky nodes determines the pipe's leak parameters.

For high sampling frequencies or large-scale problems, when the characteristic nodes and, therefore, the leak parameters are numerous, the method of leak detection can be applied step-by-step. Through a sequential procedure the distance between the leak candidate locations gets closer and closer.

REAL APPLICATION OF THE METHOD

System introduction

In this section, the proposed model is applied against a real-life pipeline. The system's information and the data gathered for leak detection are available from a field data collection program already carried out. This program was carried out jointly by Scottish Water (SW), Instituto Superior Tecnico (IST) and Universty of Perugia (UoP) for the transmission pipeline – Lintrathen East Trunk Main Network at SW (Dundee, UK) (Covas et al. 2004).

One of the branch mains of this system, namely 'Balmashanner main', has been considered herein as the case study. This pipeline is branched from 'Lintrathen East Trunk Main' with 700 mm diameter and supplies the service reservoir in 'Balmashanner' with 172.2 m tail water by gravity (Figure 4).

The branch is a 300 mm diameter ductile iron pipe, with 5,936 m length. The pipe's 'C' (Hazen Williams) coefficient is about 130, obtained from the initial calibrations using steady flow data. The pipeline profile is presented in Figure 5.

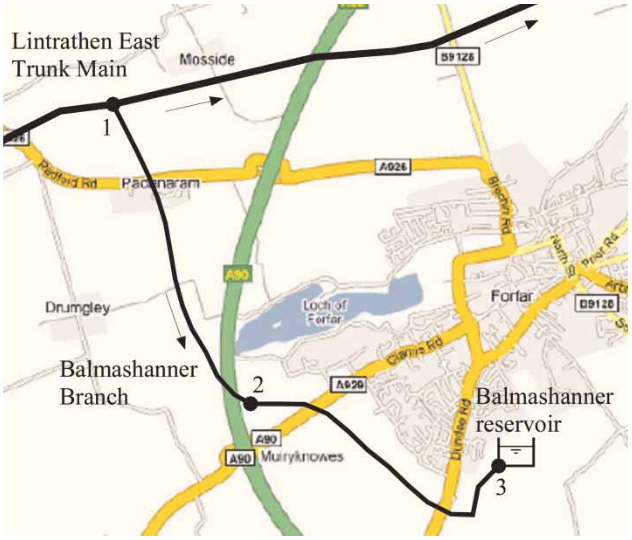

Figure 4 | Balmashanner branch main of Lintrathen East Trunk Main Network (Scottish Water, Dundee, UK).

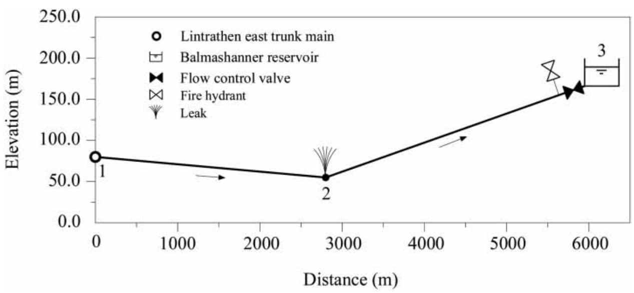

Figure 5 | Profile of Balmashanner branch main (Scottish Water, Dundee, UK).

A burst is located at about 2,900 m from the upstream junction, point 2 in Figure 5 (i.e. estimated after the application of the leak detection methodology). The leakage is from an existing scour valve with an almost 2.85 cm^2 opening area. The downstream reservoir has a Glenfield flow control valve (FCV in Figure 5), which is used to keep flows into the reservoir as smooth as possible and is usually set to operate at 30 L/s under normal conditions.

Transient generation

To apply the BTA, a transient state should be generated in the system. Theoretically, transients caused by the fast valve closure are ideal to be used in the method for leak detection, as in most transient-based techniques for leak detection. However, from a practical point of view, there are some concerns with very rapid transients inducing undesirable extreme transient pressures and increasing the effects of pipe-wall and water interaction that is not included in the standard transient analysis models. Indeed, there is a challenge in generating a useful transient to get reliable results with protecting the safety of pipe and limitations of modeling. For single pipes, one can easily determine a fast-enough valve closure considering the referred concerns. Generally, the initial steady flow in the pipe is set to a low discharge by partially closing the downstream end valve. Then, to generate a useful transient, the valve is suddenly closed. In these conditions, a transient is produced that carries information of the leak location while the amplitude of pressure variations remains within the safety limits in the pipeline. For example, in the test presented in this work the valve is initially regulated so that the initial flow is 7.7 L/s. Based on this initial flow, the valve was rapidly closed and a fast transient was generated, as seen in Figure 6. This transient flow is very informative for leak detection as well as being safe for the pipe in terms of the raised high and low pressures.

To start the test, the FCV is totally closed and a fire hydrant (FH) located immediately upstream of the FCV is opened and used to generate the transient event. At the beginning, the hydrant valve is opened to establish a steady state initial flow. Several tests were carried out (Covas *et al.* 2004). The test with 7.7 L/s initial steady flow at the end of the pipe is used herein. In order to induce the transient flow, the hydrant valve is closed as fast as possible.

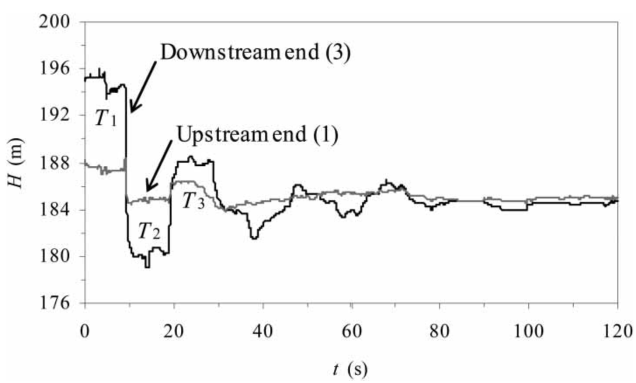

Figure 6 | Collected data in Balmashanner branch main after full closure of fire hydrant (FH).

Data measurement

After the transient flow was created, transient pressures were collected with the logging equipments from RADCOM allocated at the upstream and downstream ends of the pipe. The pressure transducer sampling frequency in this test is $fr_s = 20$ Hz. With this sampling rate (20 samples per second), the inherent leak detection accuracy is about 50 m since, in this condition, the pipe length is discretized in $\Delta x = a\Delta t \sim 1{,}000/20 = 50$ m. Based on the features of the BTA, the collected data are used here after full valve closure (Figure 6), including the pressure head variations at the upstream and downstream ends, nodes 1 and 3 in Figure 5.

Data analysis

Using the first period of the measurements at the downstream end (T_1 in Figure 6), since the theoretical period of the transient is $T_{th} = 4L/a$, the wave speed is estimated at 1,187 m/s. Considering the sampling frequency and the wave speed, it is concluded that the transient analysis grid can be developed with time step $\Delta t = 0.05$ s and the space step $\Delta x = 59.35$ m. This also means that all estimations of the leak locations include at least $\pm$ 59.35 m uncertainty.

With this information, the pipeline can be analyzed searching for leaks using BTA. For this purpose, the two approaches introduced above under Development of BTA for leak detection are applied as follows.

Direct solution

In the direct approach, only one period of measurements is enough to analyze the pipe backwardly and to detect leaks. Using the current method, it is possible to implement leak detection for different periods separately. This possibility makes the results more reliable without the need to carry out other transient tests. As seen in Figure 6, the transient signal attenuates along time mostly due to leaks and also friction losses; however, there are definitely several other dynamic effects in the system that affect the signal configuration. These effects gather more evidence and make the signal more deformed after the third period. Consequently in this work the data until the third period is considered. Using the direct solution the periods of T_1, T_2 and T_3 are separately applied for leak detection through three consecutive steps (Step I, II and III) in which the difference between candidate leaks Δx is considered to be equal to 296.8, 74.2 and 25.05 m, respectively. The results are shown in Figures 7–9 for the first, second and third periods, respectively.

The results of each period confirm those obtained for other periods. On the other hand, the reliability of the method and its results are easily investigated using the consequence periods of only one transient test. As the difference between leak candidates decreases from step 1 to 3, the recognized leak location converges to the node located at 2,800 m from the upstream end. Results seem to be satisfactory, however, due to many uncertainties and limitations in numerical simulations and because of the low sampling frequency in this test, it cannot be expected that the leak location and size is

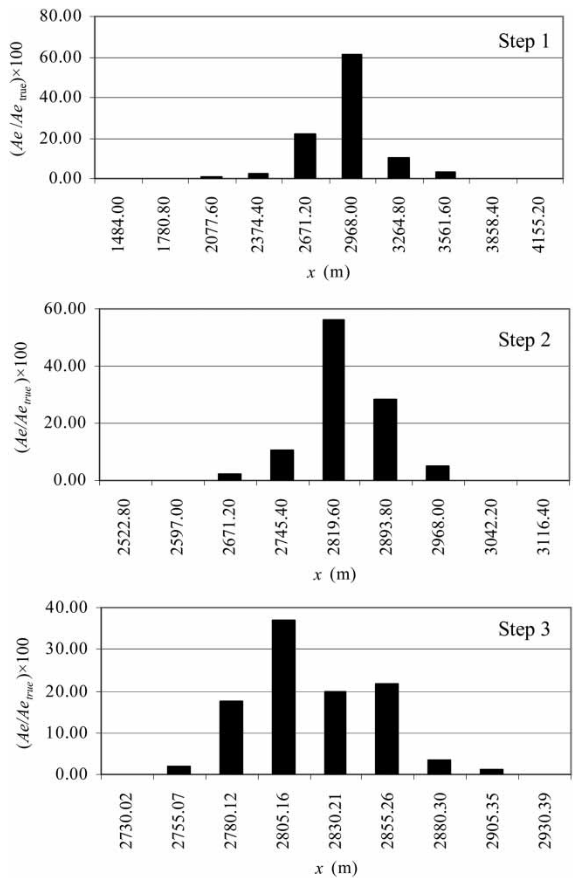

Figure 7 | Obtained results using the first period T_1.

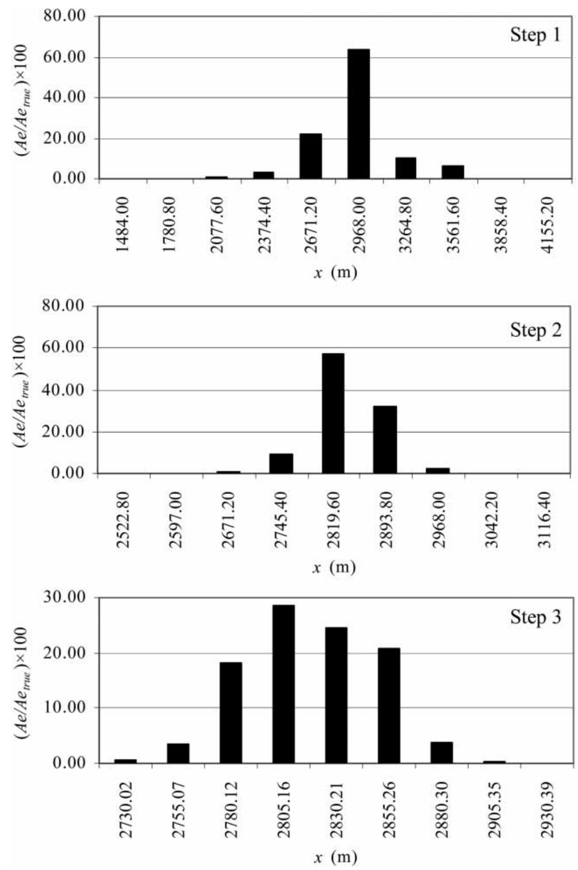

Figure 8 | Obtained results using the second period T_2.

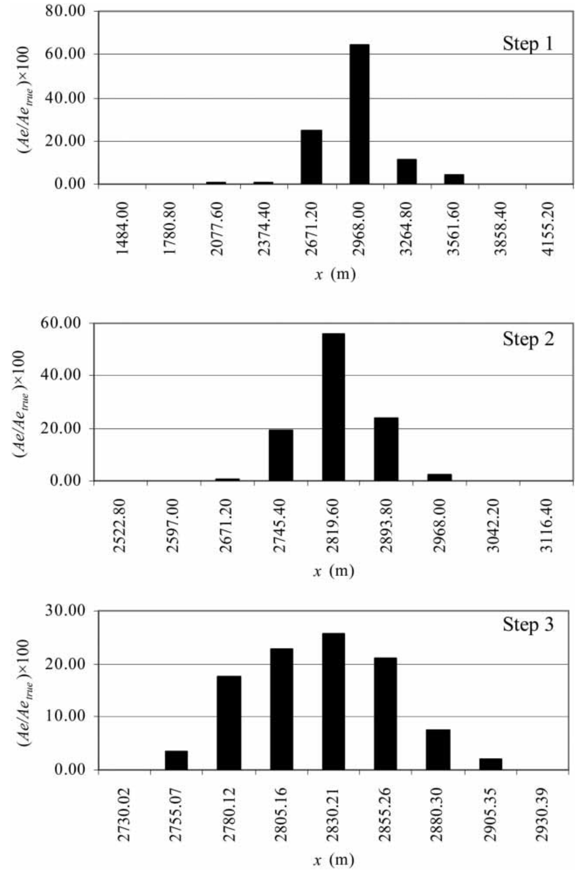

Figure 9 | Obtained results using the third period T_3.

exactly found. On the other hand, there is a leaky zone detected in the pipe located in the range of 2,780–2,855 m which is reasonably acceptable for a 6,000 m pipe length. Furthermore, the direct solution is extremely quick to perform so that the whole step-by-step leak detection procedure presented in the current example took a short time to be completed.

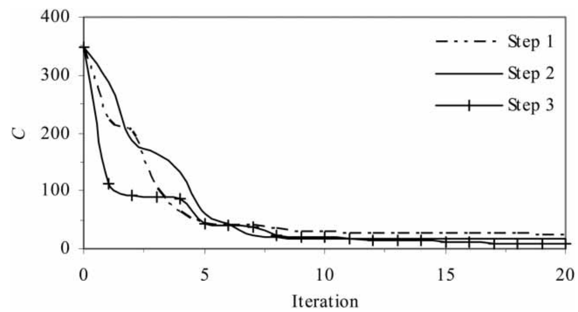

Figure 10 | Trend of minimization of objective function *C* versus iteration number.

Inverse solution

In the previous procedure, the three periods of measurements were separately applied for leak detection. Using the inverse approach, these periods can be simultaneously used. In this case, the objective function *C* (Equation (12)) is minimized by the method of SQP. This is also an alternative approach that makes the results more reliable. The inverse solution is performed in the three steps shown for the direct solution. The trend of minimization of objective function through the SQP iterations is illustrated in Figure 10 for each step.

As seen in Figure 10, the SQP is capable of dealing with the inverse problem of leak detection using BTA with a fast convergence. Obtained results from the inverse solution (Figure 11) also confirm the previous direct ones. This real life case study – Balmashanner water supply system – has

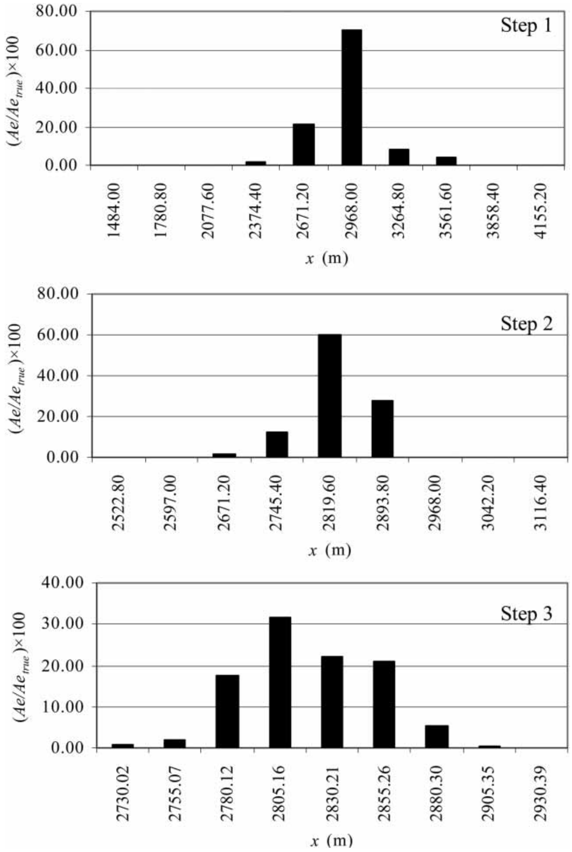

Figure 11 | Obtained results using three periods T_1, T_2 and T_3.

shown the ability of the proposed BTA to be used in real applications, applied using both direct and inverse approaches. More experimental and field tests are required for further investigating the method's merits and limitations.

CONCLUSIONS

A new model-based method has been developed and applied for leak detection. In gravity single pipe systems, using a few measured data of transient pressures at the end valve, a new scheme based on the MOC was introduced for BTA in which major uncertainty sources are avoided from numerical modeling.

With the aim of leak detection in pipes, BTA was developed to calculate leak parameters directly, as well as the flow parameters. For this purpose, additional equations based on the upstream boundary conditions were combined with the BTA in a system of equations and unknown variables of leaks and flow characteristics. This system is developed and solved for each period of measurement at the downstream end. In this condition, leak areas are calculated throughout the pipe as well as the flow characteristics. Using only one period of measurement, the whole pipe can be analyzed at once for leak detection.

An alternative approach was also introduced and applied to solve the problem of leak detection in an inverse way. An objective function with a least squares criterion was defined to minimize the observed and calculated upstream heads. In this case, the leak candidate areas as decision variables are optimized using the method of SQP. Finally, leaks are located at the nodes with a non-zero value of leak area.

Transient analysis using the proposed method is entirely independent of the valve type, the method of maneuver and the closure time. There is also no need to impose initial flow boundary conditions. These benefits not only significantly simplify the modeling but also avoid major uncertainty sources of the numerical calculations, which are very important for leak detection. To omit valve modeling effects, pressure variations measured at the valve location were considered after full closure with this method applied afterward.

A real-life pipeline, the Balmashanner main, a part of Lintrathen East Trunk Main Network at SW (Dundee, UK), was analyzed in this work as a case study. Both direct and inverse approaches were applied for leak detection of the mentioned system. The consequences and step-by-step solutions made the obtained results reliable and satisfactory. This real example has shown the abilities and practicality of the proposed method.

Using the direct solution method, one stage backward analysis is enough for leak detection. Consequently, the method is very fast with very few calculations. Also, the validity of obtained results can be easily investigated by carrying out leak detection using other periods of measurements. Finally, based on the mentioned advantages of this method and the presented examples, this method of leak detection is found to be reliable, easy and shows potential to be utilized with no need to specify particular boundaries and method of operation. The method also has some limitations in practice which are addressed as follows.

Since the method needs to numerically model pipes, comprehensive data should be gathered. The assumption that leaks occur at characteristics nodes has an implicit uncertainty in the leak location of $\Delta x = \pm a/fr_s$, where fr_s is the sampling frequency. Thus, the sampling frequency should be set for the minimum required leak location uncertainty Δx, taking into account the wave speed. Data uncertainties and errors in measurements, which are typical of any monitoring process, can lead to some inaccuracies in the leak location and sizing. The generated transient pressures should not violate the safe limits of positive and negative pressures tolerable by the pipe. This implies some concerns in specifying the initial flow and should be supervised by a hydraulic engineer with knowledge of transients. Also, if two leaks are very close to each other, the method may point to a single equivalent leak location and size. However, independently of the leak location uncertainty, the proposed BTA methods points to a leak location area, which allows the use of other leak detection equipment (e.g. acoustic correlators or accounting stethoscope) to more accurately locate the leak and to dig for pipe repair.

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