Application of hydraulic transients for leak detection in water supply systems

D. Covas*, H. Ramos*, N. Graham and C. Maksimovic****
* Civil Eng. Dept., Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
(E-mail: *didia.covas@civil.ist.utl.pt*; *helena.ramos@civil.ist.utl.pt*)
** Civil and Environ. Eng. Dept., Imperial College, Imperial College Road, SW7 2BU, London, UK
(E-mail: *n.graham@ic.ac.uk*; *c.maksimovic@ic.ac.uk*)

Water Science and Technology: Water Supply **Vol 4 No 5–6 pp 365–374** © IWA Publishing 2004

Abstract The current paper reports the investigation of two transient-based techniques for leak detection in water pipe systems using physical data collected in the laboratory and in *quasi*-field conditions. The first is the analysis of the leak reflected wave during a transient event and the second is inverse transient analysis (ITA). This was approached through the development of an inverse transient analysis tool and the collection of transient data for the testing and validation of this model. Two experimental programmes were carried out at Imperial College and in cooperation with Thames Water for the validation and testing of these techniques. Evaluation of the presence, location and size of leaks was carried out using the collected data. Transient-based techniques have been shown to be successful in the detection and location of leaks and leak location uncertainties depended on the leak size and location, flow regime and location where the transient event was generated. These leak detection methods are very promising for identifying the general area of the trunk main with leakage, and can be combined with other leak location techniques (e.g. acoustic equipment) to more precisely pinpoint the leak position. Transient-based techniques are particularly important for the diagnosis, monitoring and control of existing water supply systems, not only to detect leaks, but also to better understand the causes of pipe bursts and accidents, particularly when these are due to natural transient events.

Keywords transients; inverse analysis; leak detection; leakage; water systems

Introduction

In the last decade, changing climatic conditions and high temperatures have led to shortages and water restrictions in many countries. As a result, *leakage control* and *demand management* have become high priorities for water supply utilities and authorities. This is not only because there was greater understanding of the economic and social costs associated with water losses, but also to use as best as possible the natural resource that is *water*. Current methods of detecting and locating leaks are labour-intensive and often imprecise. Acoustic equipment (e.g. acquaphones, geophones and noise correlators) is the main type of leak detection technique used by the water industry, although there are other alternative methods (e.g. thermography, ground-penetrating radar, tracer-gas and video inspection). None of these techniques has proven yet to be totally successful. Most are particularly adequate to pinpoint leaks in a limited area of the pipe system and cannot be used in long pipelines. Additionally, acoustic equipment is considered satisfactory for leak detection in metal pipes, but its effectiveness is not well understood and documented for plastic pipes (Hunaidi *et al.*, 1998, 1999).

The continuing and urgent need for novel methods of detecting, locating and quantifying leaks in water supply systems led the authors to investigate two transient-based techniques (Covas, 2003): (i) the identification of the leak reflected wave during a transient event and (ii) inverse transient analysis. This paper presents the assessment of the application of these two techniques for leak detection using physical data. Extensive experimental programmes were carried out at Imperial College (London, UK) and in cooperation with Thames Water (London, UK) to collect the necessary data with and without simulated leaks. Leak detection was carried out using the referred two techniques. The application of these methods in the field is discussed.

Experimental data collection

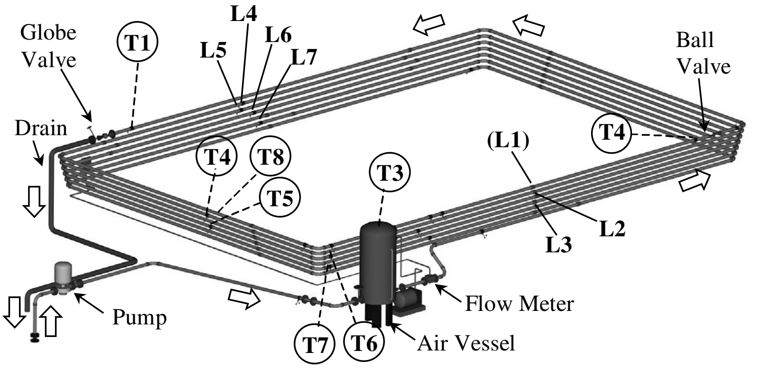
Two experimental programmes were carried out at Imperial College (IC) and in cooperation with Thames Water (TW), designed to collect reliable data sets with and without simulated leakage for the investigation of transient-based leak detection, location and sizing techniques.

Imperial College laboratory data

The first set of tests was carried out using a specially constructed, 277 m pipeline at Imperial College London (Figure 1) – (Covas, 2003). The pipe was made of high-density polyethylene (PE) with 50.6 mm inner diameter and 277 m long. The rig included a pump and a pressurised vessel at the upstream end, and a globe valve at the downstream end. This valve was used to control the flow and to generate the transient. An electromagnetic flow meter was used to measure the initial flow. The data acquisition system (DAS) was composed of an acquisition board (with 8 channels and a maximum sampling frequency of 9,600 Hz per channel), 8 pressure transducers (Ti) and a computer. Transducers had an absolute pressure range from 0 to 10 bar and accuracy of 0.3% of full range. Transient tests were run for a wide range of flow-rates, from laminar ($Q_0 = 0.05$ l/s; $Re = 1{,}400$) to smooth turbulent regimes ($Q_0 = 2.0$ l/s; $Re = 50{,}000$), with and without simulated leaks. Seven leak locations (Li) were used with five leak sizes (Table 1).

Thames Water quasi-field data

The second set of tests was carried out in the world's longest experimental PE pipeline (TORUS pipe) with 1.3 km length, located Kempton Park, Thames Water, London (Figure 2). The system consists of two main pipes: (i) an inlet pipe starting at an upstream reservoir with two submersible pumps, 90 m long and made of medium-density PE (MDPE) with 70 mm ID; and (ii) the main pipe, 1.2 km long, buried underground, made of MDPE with 108 mm ID. The main pipe rises above ground at three points 500 m, 900 m and 1,300 m (from the upstream end) and passes through a 25 m testing station. A gate valve was used to



Section	Dist. from Air Vessel
Pump	(5.0)
T3	0.0
Leak 7	66.0
T7	80.0
Leak 3	82.9
T5	116.4
Leak 6	146.3
T6	160.3
Leak 2	162.5
Leak 5	187.1
T8	196.9
Leak 4	227.4
T4	237.5
T2	245.4
T1	270.0
GV	271.8

Figure 1 Imperial College (IC) experimental facility (Covas, 2003)

Table 1 Summary of the experimental tests at IC experimental facility (Covas *et al.*, 2002)

Test Case	Downstream Flow Range (l/s) [Reynolds Number Range]	Leak discharge (l/s) [Leak orifice size (mm)]
No Leak	0.05 l/s–2.0 l/s [1,400–50,000]	–
Leaks: L1, L2, L3, L4, L5	0.05, 0.10, 0.25, 0.50, 0.75, 1.0, 1.25, 1.5 (l/s) [1,400–38,000]	0.1, 0.23, 0.34, 0.45, 0.55 (l/s) [2.3, 3.5, 4.15, 5, 5.4] (mm)

control the flow and a butterfly valve (BV) to generate the transient. The flow was measured in an electromagnetic flow meter. The DAS was the same as used in the IC tests.

Transient tests were run for several steady state flows ($Q_0 = 0.9$, 2.0, 2.3, 2.5 and 3.1 l/s) corresponding to smooth turbulent regime. Tests were carried out with and without simulated leakage. Leaks were simulated with side outlet gate or ball valves used only to operate fully opened or closed. These were installed at two locations of the pipeline inside the portakabin, L1 and L2, respectively, at *ca.* 473 m and *ca.* 876 m from the upstream end. Two leak sizes were simulated by small reduction orifices screwed to the valves ($Q_{L0} = 0.35$ and 0.65 l/s).

The effect of a leak in transient pressure signal

Leak travelling wave

When a sudden pressure surge is induced in a pipe system, discontinuities like leaks, changes of pipe diameter or material, tee-junctions, local head losses or air pockets, introduce changes in the hydraulic transient event propagation. A leak creates a pressure drop; a dead-end or a closed-valve reflects totally an incident wave; an air bubble creates a pressure drop followed by a pressure increase. The detection of these signals allows their identification and location.

In a pressurised pipe with a constant flow rate, an instantaneous change in flow conditions ΔQ induces a pressure variation ΔH given by the Frizell-Joukowsky formula: $\Delta H = -a/g\Delta Q$. This surge propagates along the pipe and, at every discontinuity, part of the incident wave is reflected backward. A leak induces a sudden pressure drop ΔH_r in a positive pressure surge ΔH. For fast changes in flow conditions, this inflection can be identified in the pressure signal. The distance of the leak from the source of the transient, X_D, can be estimated based on the travelling time t^* of the transient to the leak and to return to the source (see Eq. (1)).

Theoretical formulas based on the classic waterhammer theory have been developed for the estimation of the leak size for the manoeuvre of closure of an inline-valve (Brunone, 1999; Covas and Ramos, 1999). One of these will be used herein (see Eq. (2)). These are

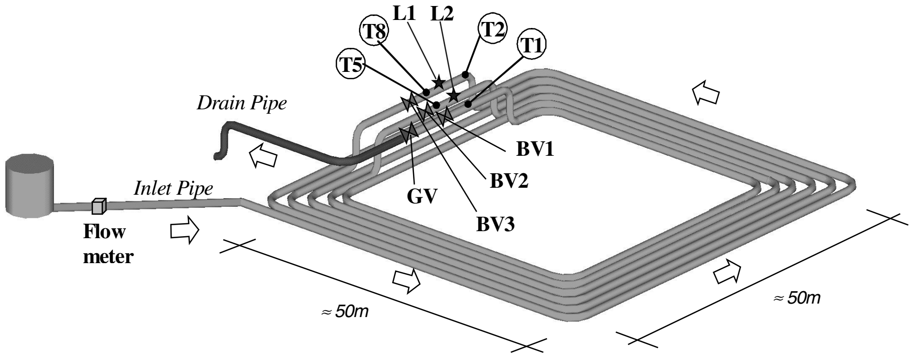


Figure 2 Thames Water TORUS pipeline (Covas, 2003)

mere reference formulas for preliminary estimation of leak sizes (Covas, 2003), as they do not accurately describe the behaviour of real systems, due to friction losses (in general) and the viscoelastic behaviour of the pipe (in plastic pipes).

$$X_D = at^*/2 \tag{1}$$

and

$$q = \frac{Q_{L0}}{Q_0} = \frac{\Delta H_d}{\Delta H}\left[1 - \sqrt{1 + \frac{\Delta H + (\Delta H_d/2)}{H_0 - H_{Lout}}}\right]^{-1} \tag{2}$$

where H_0 = steady-state piezometric-head at the leak section (considering the pipe axis horizontal and negligible friction losses); H_{Lout} = piezometric-head outside the leak (if free discharge to the atmosphere, $H_{Lout} = Z_L$); ΔH = the pressure variation at the section where the surge is generated (if upsurge, $\Delta H > 0$); ΔH_d = sudden pressure variation induced by the leak at the waterhammer valve section (if upsurge, $\Delta H_d < 0$; otherwise, $\mathrm{sign}(\Delta H) = -\,\mathrm{sign}(\Delta H_d)$).

Imperial College pipeline

Data collected at the IC pipeline with simulated leakage were used to test the travelling wave technique for leak location and sizing. A selected set of data corresponding to three leak locations (L2, L3, L4) and three sizes ($D_L = 2.7$, 4.8 and 6.0 mm) for the downstream flow $Q_0 = 1.0$ l/s was used to investigate the leak travelling wave principle (Covas, 2003).

Three methods were used for the estimation of wave speed: (I) classical formulas; (II) Fourier analysis; and (III) the travelling time between transducers. Wave speeds calculated by (I) are 10 to 20% lower than those estimated based on the pressure signal by (II), (III).

Leak locations X_D calculated by Eq. (1) are presented in Table 2. Leak location can be accurately pinpointed by (III) (i.e. $\varepsilon_{loc} = 0.3\%$ to 5.5%); the location error decreases with the leak size increase and the distance from downstream decrease. Methods (I) and (II) have higher uncertainties due to inaccurate wave speed estimates (i.e. $\varepsilon_{loc} = 0.5\%$ to 13.0% and $\varepsilon_{loc} = 0.8\%$ to 6.4%, respectively). Obtained leak location uncertainties are satisfactory, as these are less than 15% of pipe length. Leak sizing errors ε_{size} are much higher ($\varepsilon_{size} < 80\%$) than leak location errors ε_{loc} (Table 2), as Eq. (2) does not account for frictional and mechanical losses.

Figure 3 presents the time variation of the dimensionless piezometric head $(H - H_0)/(H_{max} - H_0)$ for several case-tests. Figure 3a shows the effect of the leak size and Figure 3b illustrates the effect of the leak location for the same downstream flow-rate.

Thames Water pipeline

Data collected at the TW pipeline with simulated leakage were analysed. Transient tests for two leak locations (L1 and L2) and two sizes, and $Q_0 \sim 2.0$ l/s and ~ 2.7 l/s were analysed. Methods (I) and (III) were used for the estimation of wave speed. Wave speeds calculated by theoretical formulae (Method I) were 2/3 ($a = 225$ m/s) of those observed in the actual pressure signal by Method (III) ($a \sim 320$ m/s). Leak locations and sizes and respective errors are presented in Table 3. ε_{loc} decreases with the increase of wave speed, from Methods (I) to (III). ε_{loc} and ε_{size} decrease with the increase of the leak size, but not with the decrease of the distance of the leak from downstream X_D. Leak location can be accurately pinpointed by (III) ($\varepsilon_{loc} \leq 1.0\%$), yet, (I) has much higher uncertainties due to inaccurate wave speeds ($\varepsilon_{loc} = 8\%$ to 18%). Leak locations are less than 13 m in 1,300 m, whereas ε_{size} are much higher ($\varepsilon_{size} < 54\%$).

Table 2 Assessment of the leak location and size by the travelling wave principle (IC)

Leak and flow characteristics					Pressure signal Readings		Theoretical formula Method (I)		Frequency analysis Method (II)		Measurements transducers Method (III)		Leak size		
Leak	X_{true} **(m)**	$A_{Lef\ true}$ **(m^2)**	Q_{L0} **(l/s)**	Q_0 **(l/s)**	T_C **(s)**	t^* **(s)**	$X = L - X_D$ **(m)**	ε_{loc} (%)	$X = L - X_D$ **(m)**	ε_{loc} (%)	$X = L - X_D$ **(m)**	ε_{loc} (%)	q**(%) by Eq. (2)**	Q_{L0} **(l/s)**	ε_{size} (%)
L3	82.86	4.24×10^{-6}	0.12	1.00	0.17	1.05	97.79	5.5	77.32	2.0	67.96	5.5	0.03	0.03	78.1
		1.21×10^{-6}	0.35		0.17	0.95	114.15	11.5	95.61	4.7	86.64	1.4	0.20	0.20	42.4
		1.89×10^{-6}	0.55		0.15	0.92	118.30	13.0	100.25	6.4	91.99	3.4	0.34	0.34	38.0
L2	162.48	4.24×10^{-5}	0.12		0.15	0.61	171.22	3.2	159.39	1.1	153.37	3.4	0.09	0.09	23.3
		1.21×10^{-5}	0.34		0.14	0.55	180.20	6.5	169.42	2.6	166.15	1.3	0.28	0.28	19.1
		1.89×10^{-5}	0.54		0.17	0.57	177.59	5.6	166.51	1.5	161.58	0.3	0.41	0.41	23.8
L4	227.38	4.24×10^{-5}	0.11		0.15	0.26	228.86	0.5	223.81	1.3	221.63	2.1	0.15	0.15	39.4
		1.21×10^{-5}	0.34		0.14	0.23	234.39	2.6	229.99	1.02	229.16	0.7	0.39	0.39	13.7
		1.89×10^{-5}	0.53		0.15	0.23	234.11	2.5	229.68	0.8	228.27	0.3	0.53	0.53	0.3

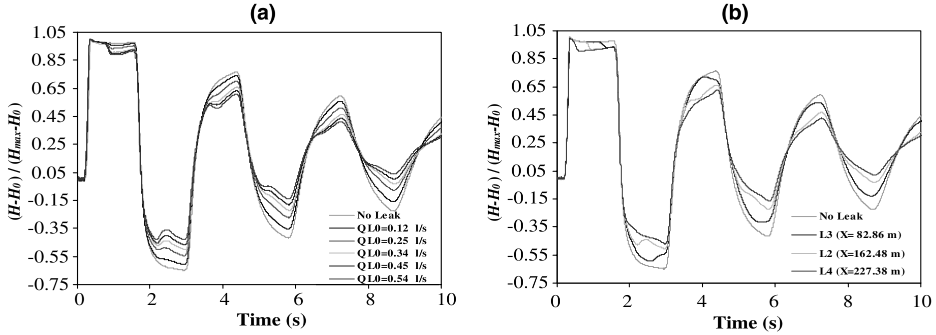


Figure 3 Dimensionless piezometric head at T1 (IC): (a) effect of the leak size (L2; $Q_0 = 1.0$ l/s) and (b) effect of the leak location ($Q_{L0} \sim 0.34$ l/s; $Q_0 = 1.0$ l/s)

Figure 4 presents the time variation of the dimensionless piezometric head during the transient event (Day 4): Figure 4a shows the effect of the leak size for $Q_0 = 2.7$ l/s and leak L1: the leak pressure drop increases as the leak size increases. Figure 4b illustrates the effect of the leak location for $Q_0 = 2.7$ l/s and $Q_{L0} = 0.65$ l/s: the leak pressure drop is smaller for the leak farer away from downstream.

Inverse transient analysis

Conceptual model

The inverse transient analysis (ITA) is used for the identification of unknown parameters such as leaks by using transient pressure data. ITA is an optimisation problem in which the system's behaviour is simulated by a Hydraulic Transient Solver (HTS) and the difference between observed and calculated variables is adjusted by an Inverse Transient Solver (ITS). ITA has been widely tested with artificial data (Liggett and Chen, 1994; Vitkovsky *et al.*, 2000; Kapelan *et al.*, 2001); however, very little evidence exists of the method validation and testing with laboratory data or field data (Covas *et al.*, 2002, 2003). The Inverse Solver (ITS) is the optimisation algorithm that searches for the best-fitted solution by minimizing the average least-square errors (ALSE) between observed and calculated variables. Observed data are pressure measurements. Unknown parameters can be leak locations, pipe roughness, decay coefficient and the creep-function. Two objective functions were used: simple least-squares (LS), and weighted least-squares (WLS). Two optimisation techniques were implemented: Levenberg-Maquardt (LM) and Genetic Algorithms (GA). A novel Hydraulic Transient Solver (HTS) was developed to calculate hydraulic transients in pressurised PE pipe systems. This model incorporates terms to take into account unsteady friction and pipe-wall Viscoelasticity.

Imperial College pipeline

The ITS was used to assess the application of this technique to locate and size of existing leaks at the IC pipe system using collected transient pressure data. The comparison between leak detection results using "linear elastic" and "linear viscoelastic" transient has shown that the "linear elastic" transient solver is very imprecise in the description of transient events in PE pipes, which hinders the correct location of leaks. In comparison, the "linear viscoelastic" transient solver (properly calibrated) accurately describes observed transient pressures, which is essential for the successful leak location and sizing (Covas, 2003).

A sensitivity analysis was carried out to assess the application of this technique for the downstream end flow-rate Q_0 of 1.0 l/s, and three leak diameters (2.7, 4.4 and 6.0 mm) and

Table 3 Assessment of the leak location and size by the travelling wave principle (TW)

Leak and flow characteristics					Pressure signal Readings		Theoretical formula Method I		Measurements between transducers Method III		Leak size		
Leak	**X_{true} (m)**	**$A_{Lef\ true}$ (m^2)**	**Q_{L0} (l/s)**	**Q_0 (l/s)**	**T_C (s)**	**t^* (s)**	**$X=L-X_D^{(*)}$ (m)**	**ε_{loc} (%)**	**$X=L-X_D^{(*)}$ (m)**	**ε_{loc} (%)**	**q(%) by Eq. (2)**	**Q_{L0} (l/s)**	**ε_{size} (%)**
Several leak locations and sizes for the same downstream flow-rate $Q_0 \sim 2.0$ l/s													
L1	473	4.44×10^{-5}	0.40	2.2	0.49	5.20	695	17.3	460	1.0	0.11	0.24	39.8
		8.51×10^{-5}	0.70	2.0	0.50	5.17	698	17.6	466	0.6	0.22	0.44	37.3
L2	876	4.44×10^{-5}	0.40	2.2	0.47	2.62	985	8.5	863	1.0	0.08	0.18	53.9
		8.51×10^{-5}	0.70	2.0	0.32	2.59	989	8.8	870	0.5	0.22	0.45	35.8
Several leak locations and sizes for the same downstream flow-rate $Q_0 \sim 2.8$ l/s													
L1	473	4.44×10^{-5}	0.35	2.9	0.48	5.12	704	18.0	461	1.0	0.08	0.24	31.8
		8.51×10^{-5}	0.65	2.7	0.48	5.08	709	18.4	465	0.6	0.16	0.43	34.5
L2	876	4.44×10^{-5}	0.30	2.9	0.52	2.65	982	8.3	855	1.6	0.07	0.19	35.8
		8.51×10^{-5}	0.65	2.7	0.40	2.58	990	8.9	872	0.3	0.14	0.37	42.4

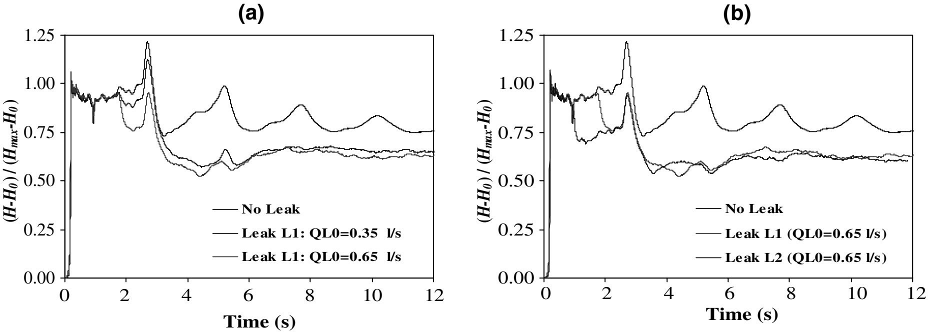


Figure 4 Dimensionless piezometric head at T1 (TW): (a) effect of the leak size (L1 and $Q_0 = 2.7$ l/s) and (b) effect of the leak location ($Q_{L0} = 0.65$ l/s and $Q_0 \sim 2.7$ l/s)

locations (82.86, 162.48 and 227.38 m from the upstream end), i.e. 9 test cases. The sample size (ΔT) used was equal to one period of the pressure wave, $T = 4L/c$ ($L =$ pipe length and $c =$ wave speed). ITA was applied in a step-wise manner, starting with a description of leak candidates sparsely distributed throughout the system and gradually defining these candidates around the main potential leak locations obtained in previous steps. Accordingly, the pipeline with $L = 271.80$ m was divided into 54 sections, equally spaced, with 5.03 m each. Results obtained for the leak with 4.4 mm diameter and at 82.86 m (Node 17) are in Figure 5.

Based on the analysis of the referred 9 test cases, the following conclusions can be drawn: (i) ITS pinpointed to the actual leak location and assessed the leak size for all analysed tests, though with different uncertainties associated with the description of leak candidates; (ii) most single leaks could be located with an accuracy of 5 m (corresponding to 1.8% of total

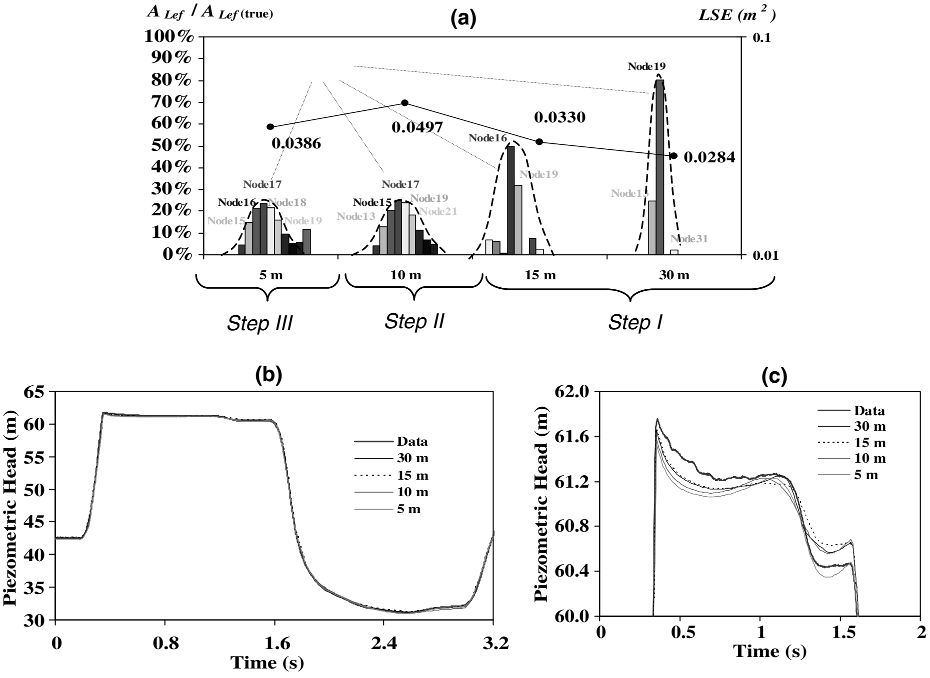


Figure 5 Inverse Transient Analysis for leak L3 ($x = 82.86$ m; Node 17), $Q_{L0} = 0.36$ l/s and $Q_0 = 1.0$ l/s: (a) optimal leak location and size; (b), (c) piezometric head at T1 – data vs. best solutions (IC)

pipe length); (iii) the most accurate leak locations and sizes were observed for larger leaks and for leaks closer to the location where the transient event was generated.

Thames Water pipeline

The objective of this section is to show how ITA performs when using data collected in *quasi*-field conditions at the TW pipeline, with several sources of uncertainty associated with the system characteristics and collected data. One example of leak detection simultaneously with creep calibration is presented. For this test, the downstream flow-rate Q_0 is 2.8 l/s and the leak is located at 473.00 m from the downstream end and has a sizes $A_{\mathrm{Lef}} = 4.44 \times 10^{-5}$ m^2 (with flow-rate ~ 0.35 l/s). Unsteady friction effects were neglected. The methodology was applied in a step-wise manner, as described in which the Step I included the definition of leak candidates equally spaced 5% and 10% of the total pipe length. Accordingly, the pipeline with $L = 1280.00$ m was divided into 61 sections, equally spaced ~ 20 m. Based on the analysis of these results, the following conclusions can be drawn: (i) as the pipeline is divided into smaller sections near the leak location, the ITS tends to spread leaks in the vicinity of the leak with a total flow-rate equal to the leak flow-rate; (ii) leaks could be located with an accuracy of 24 m, which correspond to 2% of the total pipe length.

Summary and conclusions

The evaluation of the presence, location and size of leaks was carried out using collected data. Two different approaches were analysed: identification of the leak reflected wave and inverse analysis. ITA was the most successful method, providing that an accurate transient solver was used and leak detection was carried out simultaneously with creep calibration. ITA was applied in a step-wise manner to more accurately pinpoint leaks, starting with a description of leak candidates equally spaced at 10% of the total pipe length and gradually reducing it to 2% and 1% near the potential leak locations. Leak location uncertainties depended on the leak size and location, flow regime and location where the transient event was generated; in most cases, these uncertainties were less than 2%, which corresponds to 5 m in the IC pipe and 24 m in the TW pipe. These methods are very promising for identifying the area of the supply system with leakage, and can be combined with other leak location techniques (e.g. acoustic equipment). Transient-based techniques are particularly important for the diagnosis, monitoring and control of existing water supply systems.

Acknowledgements

The results presented here were achieved through a joint research project between the University of Exeter and Imperial College London supported by the UK Engineering and Physical Sciences Research Council. The authors would like to acknowledge Ivan Stoianov for the contribution in the development of experimental programmes and the 3-D schematics of the pipelines, and to Thames Water Utilities for use of the TORUS pipe.

References

Brunone, B. (1999). Transient Test-Based Technique for Leak Detection in Outfall pipes. *Journal of Water Resources Planning and Management, ASCE*, **125**(5), 302–306.

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

Covas, D. and Ramos, H. (1999). Leakage Detection In Single Pipelines Using Pressure Wave Behaviour. *Proceedings of Water Industry Systems: Modeling and Optimization Applications, CCWI' 99*, Pub. CWS, Exeter, UK. pp. 287–299.

Covas, D., Ramos, H., Graham, N., Maksimovic, C., Kapelan, Z., Savic, D. and Walters, G. (2003). An assessment of the application of inverse transient analysis for leak detection: part II – collection and application of experimental data. *Proc. Int. Conf. on Computers and Control in the Water Industry (CCWI 2003), Imperial College London, UK*, 15–17 Sept. 2003. Balkema.

Covas, D., Stoianov, I., Butler, D., Maksimovic, C., Graham, N. and Ramos, H. (2002). Inverse Transient Analysis for Leak Detection and Calibration – A Case Study in a Polyethylene Pipeline. *Hydroinformatics 2002*, Eds. Cluckie, I.D., Han, D., Davis, J.P. and Heslop, S., IWA Publishing, London, UK, pp. 1154–1159.

Hunaidi, O., Chu, W., Wang, A. and Guan, W. (1998). Effectiveness of Leak Detection Methods for Plastic Water Distribution Pipes. *Workshop on Advancing the State of our Distribution Systems – The Practical Benefits of Research. AWWA Dist. System Symposium*, AWWA, Austin, Texas.

Hunaidi, O., Chu, W., Wang, A. and Guan, W. (1999). Leakage Detection Methods for Plastic Water Distribution Pipes. *Advancing the Science of Water – AWWA Research Foundation Technology Transfer Conference*. AWWA, Fort Landerdale, Florida, pp. 249–263 (electronic version).

Kapelan, Z., Savic, D.A. and Walters, G. (2001). Use of Prior Information on Parameters in Inverse Transient Analysis for Leakage Detection and Roughness Calibration. *Proceedings of Water Software Systems: Theory and Applications, DeMonfort University, Leicester, UK.*

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

Vitkovsky, J.P., Simpson, A.R. and Lambert, M.F. (2000). Leak Detection and Calibration Issues using Transient and Genetic Algorithms. *Journal of Water Resources Planning and Management, ASCE*, **126**(4), 262–265.