Field validation of the application of hydraulic transients for leak detection in transmission pipelines

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ABSTRACT: This paper describes an extensive field study which has been carried out to validate the application of controlled hydraulic transients (surges) for detecting and locating leaks in water transmission pipelines. A large number of publications and research projects for the last ten years have described and developed a variety of techniques which aim to use controlled transient events for detecting and locating leaks both in transmission pipelines and distribution networks. The developed techniques have been extensively tested using numerical data and experimental data from small scale laboratory facilities. To the best knowledge of the authors, there have been no published studies on the field validation of the application of hydraulic transients for detecting and locating leaks in operational water transmission and distribution systems. The authors have recently completed four full-scale field studies which aim was to assess the practicalities of using controlled transient events for detecting and locating leaks in transmission pipelines. This paper presents the field results from a water transmission pipeline operated by Essex and Suffolk Water as pressure data were collected using a specifically assembled data acquisition system (IC-DAS). IC-DAS allows high-frequency of data acquisition with sampling rates of up to 1000S/s (Samples/second) and perfect time synchronization (less than 50μs). The experiments clearly demonstrated the practical difficulties and limitations of the application of transient events for detecting and locating leaks.

1 INTRODUCTION

The application of hydraulic transients for detecting and locating leaks in water transmission and distribution systems have received significant research attention for the last ten years. A large number of publications and research projects have described and developed a variety of techniques which utilise controlled transient events. The underlying idea is relatively simple: when there is a sudden change in flow velocity, a pressure transient (known also as surge or water hammer), either of higher or lower pressure, starts propagating along the pipeline. Leaks, changes in pipe material and diameter, half closed valves and entrapped air will alter the propagation of the generated pressure transient and can cause sudden changes in its wave characteristics. Consequently, the generated pressure transient may contain sufficient information about the location and size of leaks and also various features (discontinuities) along the pipeline.

Numerical and laboratory studies (Jonsson 1995; Covas *et al.* 2000; Brunone and Ferrante 2001; Vitkovsky *et al.* 2002) show that leaks affect hydraulic transients in three possible ways: (i) leaks generate small pressure variations (reflections) during the first transient wave; (ii) leaks distort pressure peaks during subsequent pressure waves; and (iii) leaks attenuate pressure transients. As a result, the developed techniques can be broadly classified into three categories. The first category can be summarised as the travelling pressure wave analysis which uses an estimate of the wave speed and the time of arrival of the leak reflection (Brunone 1999). The second category defines the so-called inverse transient analysis (ITA) while the third category combines all other techniques based on frequency (Mpesha *et al.* 2001; Wang *et al.* 2002) or time-scale analyses ((Stoianov *et al.* 2002b). Most research attention has been given to the ITA.

The ITA is a parameter estimation technique which combines a transient solver with an optimisation algorithm as it attempts to quantify and locate leaks by minimising differences between numerical predictions and acquired data. In this way, the ITA utilises both leak reflections and pressure attenuation (Liggett and Chen 1994; Kapelan *et al.* 2000; Vitkovsky *et al.* 2000; Tang *et al.* 2001; Covas 2003). The major emphasis in the development of the ITA techniques has been on the incorporation of emerging optimisation techniques such as heuristic search, genetic algorithms and ant colony optimisation. It is the authors' belief that while such developments are exciting they cannot replace the significance of accurate, numeric-type processing methods based on data from operational systems.

To the best knowledge of the authors, there have been no published studies on the field validation of the application of hydraulic transients for detecting and locating leaks in operational water transmission and distribution systems. Jonsson (2001) presented the results of a field study on a 3,500m long underwater sewage water main with an internal diameter of 200mm and flow of approximately 20 l/s. The sewage pipeline was located on the bottom of a lake. One leak was detected and located using the travelling pressure wave technique. The detected leak had a length of 250mm and width of 8mm, and the leak flow was approximately 4 l/s or 20% of the base flow in the pipeline. It should also be noted that the pipeline had no junctions or variations in pipe diameter or material.

The lack of field verification of the application of hydraulic transients for detecting and locating leaks has led to some overoptimistic conclusions derived from small scale experimental facilities. It was the purpose of a recently completed three-year project at Imperial College London (Graham *et al.* 2003) to assess the practicalities of using controlled transient events for detecting and locating leaks in water transmission pipelines and distribution networks. During the course of the project, a comprehensive experimental programme was completed by the authors which included: (i) laboratory experiments at the specifically built 271m long high-density polyethylene pipeline at Imperial College London (IC-Rig), (ii) semi-field experiments at 1.3km laboratory pipeline operated by a UK water company; and (iii) four full-scale field experiments on three operational transmission pipelines and one distribution network.

This paper describes one of the completed four field studies. The presented case study is a water transmission pipeline operated by Essex and Suffolk Water, and it has a total length of 22.7 km and an outside diameter of 860mm (33" $^{7/8}$).

2 PRELIMINARY SURVEY AND PROBLEM DEFINITION

During the process of selecting suitable sites for field testing, around 12 operational water transmission pipelines were reviewed using GIS data. The survey aimed to identify and classify topological characteristics, pipe diameter and material, flow and operational regimes, and possible access points for the installation of the data acquisition system. The study does not claim to cover all possible cases but it does provide a comprehensive idea of the challenges in setting up, testing and the possible use of controlled hydraulic transients for detecting and locating leaks. It is surprising that such a survey has not been previously carried out and the majority of scientific publications are based on highly theoretical cases without considering the practical needs and characteristics of operational systems. The systems which were included in the survey were both rural and urban transmission pipelines, and the results can be summarised as following:

- The water transmission pipelines are branched systems with a relatively high number of live connections and branches (on average 9 for the surveyed pipelines). Only one pipeline was a simple pipeline system;
- The minimum diameter for the surveyed pipelines was 406mm ID (16") as the majority of the transmission pipelines had a diameter ranging between 762mm ID (30") and 1143mm (45"). There were frequent changes in pipe diameter, material and even profile;
- The flow for these pipeline systems was between 250 l/s and 650 l/s. The average length was 12km as it varied between 5 and 27km;
- The pipe materials were predominantly cast iron, ductile iron and carbon steel as nearly all of the surveyed pipelines were more than 20 years old;

- The majority of leaks have occurred in joints. Very few leaks were larger than 4 l/s and these leaks were quickly detected. The practical interests of the water operators were to detect, quantify and locate leaks less than ~ 2 l/s or ideally seeping leaks of several litres per minute before they evolve into larger leaks;
- Two acoustic techniques were under pilot tests for inspecting transmission pipelines. The first one was SAHARA provided by PII Waterline Services and the second one was the product of a joint research project between Yorkshire Water and QinetiQ Ltd. Both techniques claimed leak detectability of significantly less than 2 l/s and location accuracy of ~1 m;
- There was a large variability in the operational regimes of the surveyed water transmission pipelines. Some of the pipelines were operated continuously with small flow variations, while others were controlled by the level of the down-stream reservoir. In all cases surge protection devices were installed to minimise pressure variations during operational changes; and,
- All water operators were reluctant to introduce sudden flow variations in their systems because of pressure transients and potential disturbance in their water treatment plants.

During the preparatory process, a sophisticated data acquisition system, named IC-DAS, was assembled for the field tests as the commercially available transient loggers (such as Technolog Newlog CV) have a maximum sampling rate of 10 S/s (Samples per second) and cannot provide time synchronisation between measurement points. The following section provides a brief description of IC-DAS.

3 DATA ACQUISITION: IC-DAS

The results from an extensive laboratory programme carried out by the authors (Stoianov *et al.* 2002a) demonstrated that high-frequency time-synchronised data collection of pressure signals from several remote locations might resolve problems with low signal-to-noise ratio (data filtering), improve significantly the accuracy in locating leaks based on the analysis of the travelling pressure wave and also would allow the use of measurements as boundary conditions in a transient solver. An interesting problem was how to define the sampling rate of capturing the pressure transients in field. As far as capturing maximum and minimum pressure of an oscillating hydraulic transient is required, the sampling rate of 10 S/s (a commercial logger) satisfies the Nyquist frequency for a long pipeline defined by the period of the generated pressure wave. However, as the field studies aimed to test a range of techniques which rely on accurately defining a leak reflection and the time of arrival of that reflection, the sampling rate was defined by the spatial resolution required for capturing a travelling wave (~ 1000 m/s) rather than a standing wave. Having taken into consideration the requirements for accurately capturing travelling reflections together with limitations in terms of data capturing, processing and storage, the maximum sampling rate for IC-DAS was set up at 1000S/s. The sampling rate used for the field tests was defined at 400S/s. This meant that in theory the spatial uncertainty in locating the leak due to the sampling rate would be around 3m.

The problem of time synchronisation between measurement points has been resolved by using a GPS (Global Positioning System) time reference to precisely timestamp and trigger data acquisition events. Laboratory tests using a signal generator showed that a time synchronisation of less than 50 μs can be successfully maintained between remote measurement points. The achieved time synchronisation is an order of magnitude higher that the required for a maximum sampling rate of 1000S/s. The assembled IC-DAS data loggers are programmable, IP68, battery operated and can store 17 hours of data when sampling at the maximum frequency of 1000S/s (43 hours at 400S/s) from two channels (Stoianov *et al.* 2003). This is only limited by the size of the currently used CompactFlash memory card (256 MB). The GPS time triggers facilitated the process of data collection as numerous experiments had been carried out throughout a 24 hour cycle without the presence of staff during the survey.

4 CASE STUDY

The water transmission pipeline, referred in this paper as *Pipeline A*, was chosen as a test site because of the relatively low number of live connections, available access points and only one change in pipe diameter and material. Valves with diameter of 50mm (2" BSP) were installed directly onto the pipeline at several access points. They provided (i) ideal conditions for eliminating signal noise or dampening due to the installation of measurement equipment; and (ii) flexibility in simulating leaks with various sizes.

The transmission pipeline connects a water treatment plant and a pumping station (two variable speed 500kW pumps) with a reservoir. The pipeline is made of carbon steel lined with bitumen and it has an external diameter of 860 mm (33"$^{7/8}$), wall thickness of 8mm and a total length of 23.14 km. The average flow rate is around 515 l/s. Essex and Suffolk Water provided a digital description of the topology of the pipeline which included the pipeline and its characteristics such as material and diameter, known branches, connections and features such as air valves, valves, bypasses, access points, wash outs, etc. The digital topology of the pipeline was combined with data from the Ordnance Survey (the Land-Line.Plus digital map) and Land-Form Panorama Contour (digital heights) in ArcView GIS. The elevation data were used to build a digital terrain model from which an approximate longitudinal profile of *Pipeline A* was derived.

After a detail analysis, it was decided to select a section of the pipeline (Figure 1) with a length of 7,395 m for the installation of data loggers and simulation of leaks. There were no branches or connections between access points 7 and 11, and there were four branches between points 2 and 7. As these branches were connected to large customers with intermittent demands or reservoirs it was made sure that the tests were carried out during hours of no demand which was achieved by setting up time triggers at the IC-DAS units.

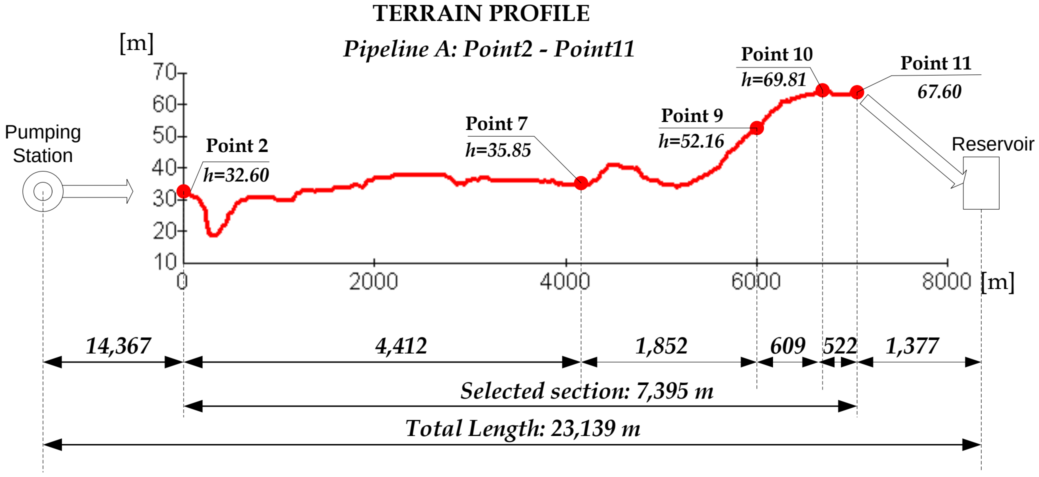

Figure 1. Terrain profile of the selected section of the pipeline

A range of tests were carried out over a period of four days. The location of measurement equipment and simulated leaks for the completed experimental sets are summarised in Table 1.

Table 1. Designed and completed experimental sets at *Pipeline A*

Experimental Sets	**Point 2**	**Point 7**	**Point 9**	**Point 10**	**Point 11**
Set 1	IC-DAS3 + NEWLOG*	IC-DAS2 + PRIMAYER*	Leak	Not Used	IC-DAS1 + PRIMAYER*
Set 2	Not Used	Transient Source	IC-DAS2	Leak	IC-DAS1

*Commercial transient loggers that were used together with IC-DAS for comparison

The first experimental set (Set 1) aimed to validate the use of regular operational changes such as pump trips for detecting leaks using the generated pressure transients. While the number of tests for the first experimental set was limited because of concerns for disrupting the water treatment process, the second experimental set was designed to test the use of alternative transient sources (a sudden discharge at access points) for detecting leaks.

During the experimental tests, a GPS survey using LEICA GPS-System 300 was carried out for access points (AP) 2, 7, 9, 10 & 11 (Figure 3a). The elevation information was required for the calibration of the hydraulic model. Data were recorded over a period of one hour at each point with a sampling rate of one reading every 5 seconds. The acquired data were processed together with data from the National GPS network for achieving high accuracy in x,y,z coordinates. GPS 3D positioning and Ordnance Survey maps use different models for the earth and coordinate systems, therefore, geodetic transformations based on National Grid Transformation OSTN02 were carried out to transform GPS ETRS89 coordinates to OSGB36 National Grid. However, the heights obtained from the GPS survey were kept in ellipsoidal (OSGB36) heights and not transformed to heights above mean sea level (Ordnance Datum Newlyn). Thus, the elevation data has a very high relative accuracy (less than 3 cm) between points 2, 7, 9, 10 & 11. Table 2 presents the results for the error in the relative elevation of the access points.

Table 2. Comparison of relative elevation difference for the access points obtained from ODN and GPS Survey

Access Points (AP)	Ordnance Survey (ODN) [m]	Height Difference between points [m]	GPS Survey (Ellipsoid heights) [m]	Height Difference between points [m]	**Difference GPS-ODN [m]**
		[1]		[2]	**[1] - [2]**
2	32.10		32.60		
7	34.75	2.65	35.45	2.85	**0.20**
9	49.20	14.45	51.31	15.86	**1.41**
10	62.50	13.30	69.51	18.20	**4.40**
11	62.75	0.25	67.10	-2.41	**abs (2.66)**

The results of the GPS survey show that elevation data obtained from Ordnance Survey Maps should not be used for the calibration of hydraulic solvers as it may contain significant errors. If an accurate hydraulic model (both steady-state and transient) is required then a GPS survey should be carried out, thus reducing uncertainties in elevation data. The Ordnance survey states that the accuracy of the contours is in the order of ±3.0 m root mean square error (RMSE). In our case, the maximum relative difference in elevation between two points was 4.40 m.

4.1 *Experimental set 1*

The goal of the first experimental set (Set 1) was to use regular operational changes such as pump trips for generating hydraulic transients, and detecting and locating leaks. A step pulse (a controlled pressure transient) was introduced by switching off/on pumps at the pumping station. Two tests (tests 1 & 2) were carried out with a complete shut off of both pumps (~ 515 l/s) and three tests (tests 3, 4 & 5) with switching off/on only one pump (~ 150 l/s). Switching off/on both pumps is a very unusual event in the operation of *Pipeline A*, while switching off/on one pump can be considered a relatively regular operational change. Each cycle of switching off/on both pumps had duration of approximately 4 minutes in order to minimise effects on the operation of the water treatment works. Leaks with various sizes were generated for tests 2, 4 and 5, while tests 1 and 2 provided the "surge signature" for a non-leaking pipeline.

Leaks with various flows and discharge to atmosphere were simulated at AP9 by using specifically manufactured orifices with diameter of 15, 20 and 30mm (Figure 2). The leak flows were calculated from the orifice equation and for a measured pressure of 2.16 bar these were:

(i) ~2 l/s or 0.4% of the base flow for an orifice of 15mm (Figure 2c) ; (ii) ~ 4 l/s or 0.8% of the base flow for an orifice of 20mm (Figure 2b); and, ~ 9 l/s or 1.8% of the base flow for an orifice of 30mm (Figure 2a).

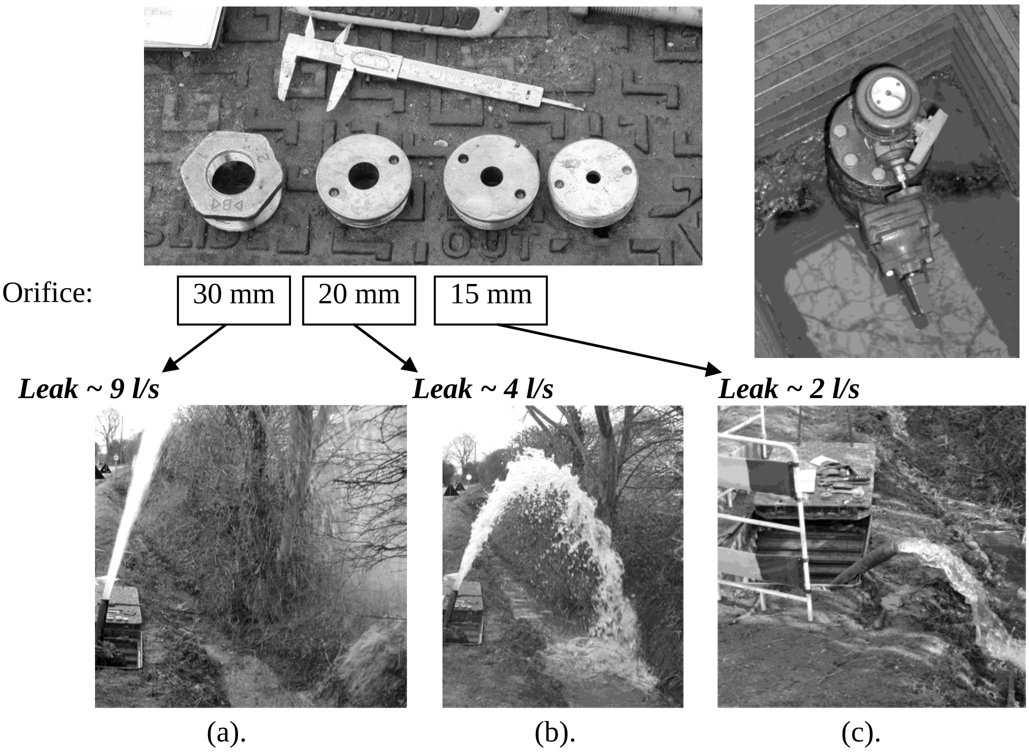

Figure 2. Simulating leaks at access point 9

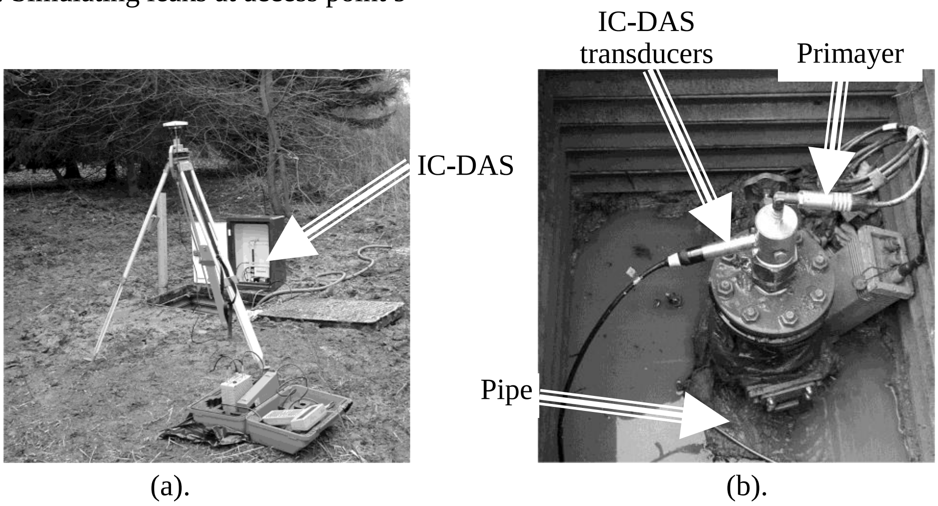

Figure 3. Installation of IC-DAS at AP 7: (a) LEICA GPS station during the geodetic survey & the mini-cabin for housing the IC-DAS, (b) installation of IC-DAS and Primayer.

The pressure transducers were installed on custom made adaptors designed to release entrapped air which is essential for dynamic testing. The IC-DAS units (DAS + pressure transducer – DRUCK PMP4000, absolute accuracy of 0.04%FS, 0-10bar) were calibrated before and after field tests using a Budenberg dead weight scale. Access points 7 and 11 were also equipped with ultrasonic flow meters with a dynamic response of 70ms. The data from the pressure transducers and the flow meters were logged by IC-DAS.

The piezometric head and flow for test 1 acquired at AP7 is shown in Figure 4a, while Figure 4b shows the piezometric head and flow for test 3 (AP7).

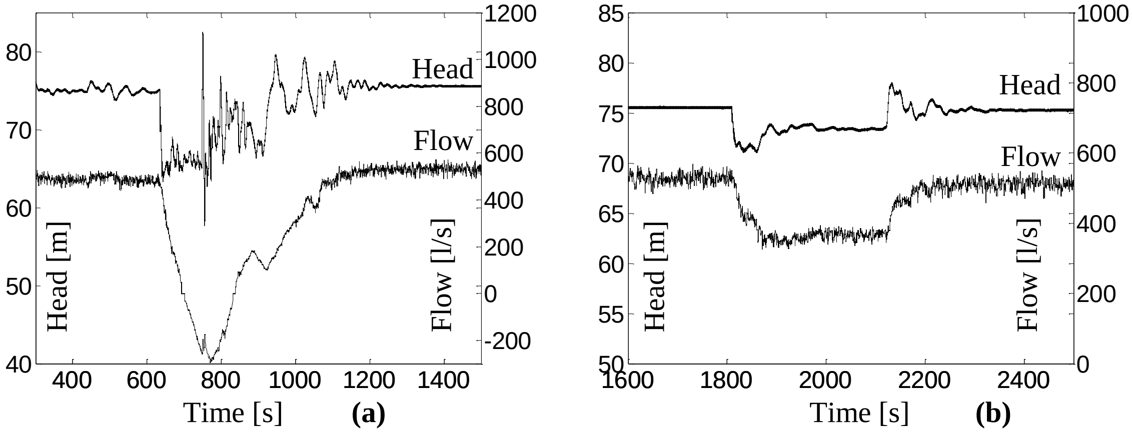

Figure 4. Piezometric head and flow acquired by IC-DAS at AP7: (a) Transient generated by switching off/on two pumps; (b) Transient generated by switching off/on one pump

The piezometric head acquired at all three measurement points (AP2, AP7 and AP11) for test1 (switching off/on two pumps) is shown in Figure 5a. The synchronised pressure measurements, detail of which is shown in Figure 5b, were used to measure the speed of propagation of the pressure wave. The measured wave speed was ~ 1010 m/s for the section between AP2 and AP7, and ~ 1000m/s for the section between Ap7 and AP11. The calculated wave speed was ~ 1135 (Wylie *et al.* 1993).

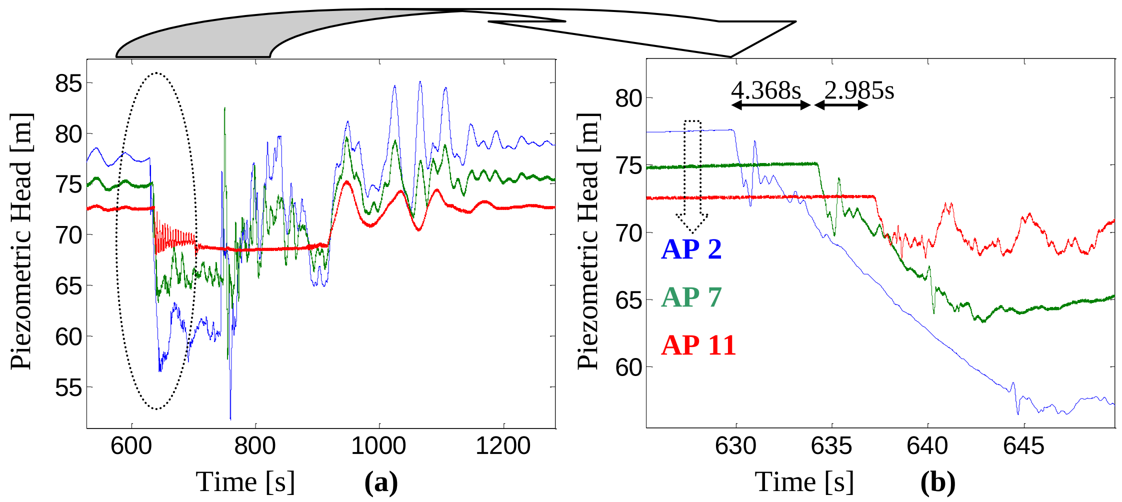

Figure 5. Piezometric head measured at three locations (AP2, AP7, AP11) for test1 (switching off/on two pumps): (a) switching off/on two pumps; (b) detail for switching off.

The controlled leak cases were compared with the response acquired during tests 1(two pumps being switched off/on) and 3(one pump being switched off/on). As there were limitations on the number of pump trips that can be generated, it was decided that a leak of ~ 2 l/s (Figure 2c) will be simulated for test 2 (two pumps) and leaks with flows of ~ 4 l/s (Figure 2b) and 9l/s (Figure 2a) will be simulated for tests 4 and 5 respectively.

The comparison between test 1 and test 2 for the piezometric head measured at AP7 for the sudden switch off of both pumps is shown in Figure 6. The acquired pressure responses (tests 1&2) were very similar and did not show any traces of leak signatures or variations in pressure attenuation. A comparison for switching on the pumps for the same case is not provided in the paper as the two pumps were switched on in a sequence and this created a very different pressure response.

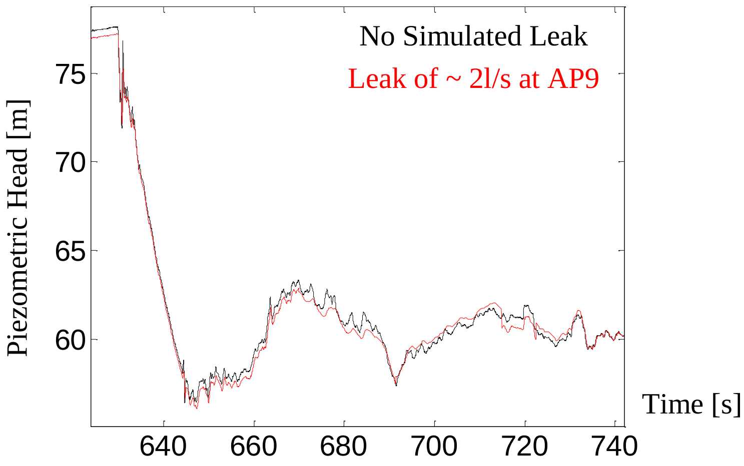

Figure 6. Comparison between no-leak (test1) and leak (test2) cases for switching off both pumps. Leak with a flow of ~2l/s simulated at AP 9.

In test 4, the flow of the simulated leak (AP9) was increased to 4 l/s (Figure 2b). The comparison between tests 3 and 4 for the piezometric head measured at AP7 for the sudden switch off and switch on of one pump is shown in Figure 7a and Figure 7b respectively. Similarly to Figure 6, the leak of 4 l/s (~0.8% of the base flow) did not affect the pressure response. There were neither new leak reflections nor difference in the pressure attenuation in any of the measurement points.

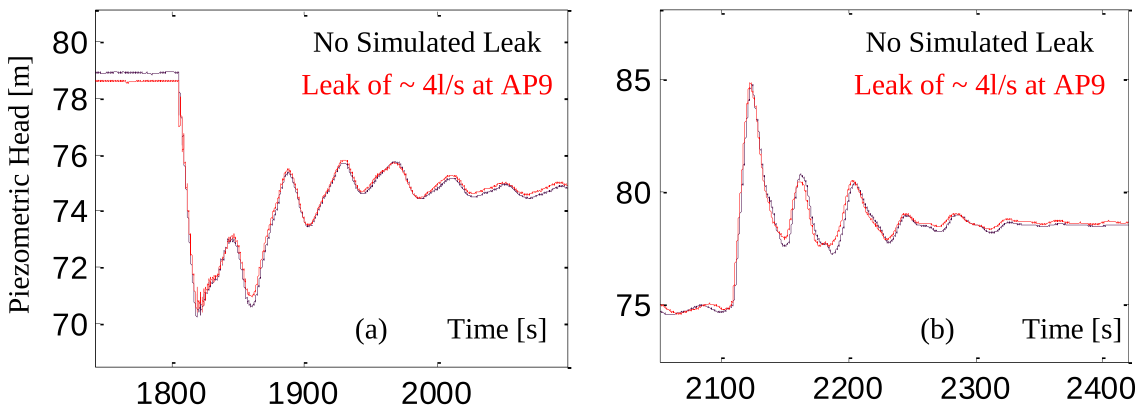

Figure 7. Comparison between no-leak (test3) and leak (test4) cases for switching off/on one pump. Leak with a flow of ~4 l/s was simulated at AP 9: (a) one pump being switch off; (b) one pump being switched on.

In test 5, the leak flow at AP9 was increased to 9 l/s (Figure 2a) which was ~1.8% of the base flow. The results for switching off one pump (Figure 8a, detail shown in Figure 8c) clearly illustrate that even a very large leak of 9 l/s cannot be detected in the particular pipeline system using regular operational variations. When the pump was switched on again, significant variations in the measured pressure profiles were observed. The variations were not directly caused by the leak. Numerical simulations confirmed that (i) the significant pressure variations in test 5 and the phase shift were caused by a pocket of entrapped air at an air valve located within 5m from AP10; and, (ii) that the pressure drop generated by a test preceding test 5 was the cause for the air valve to let air in the system and then not being able to release the air over a period of half an hour.

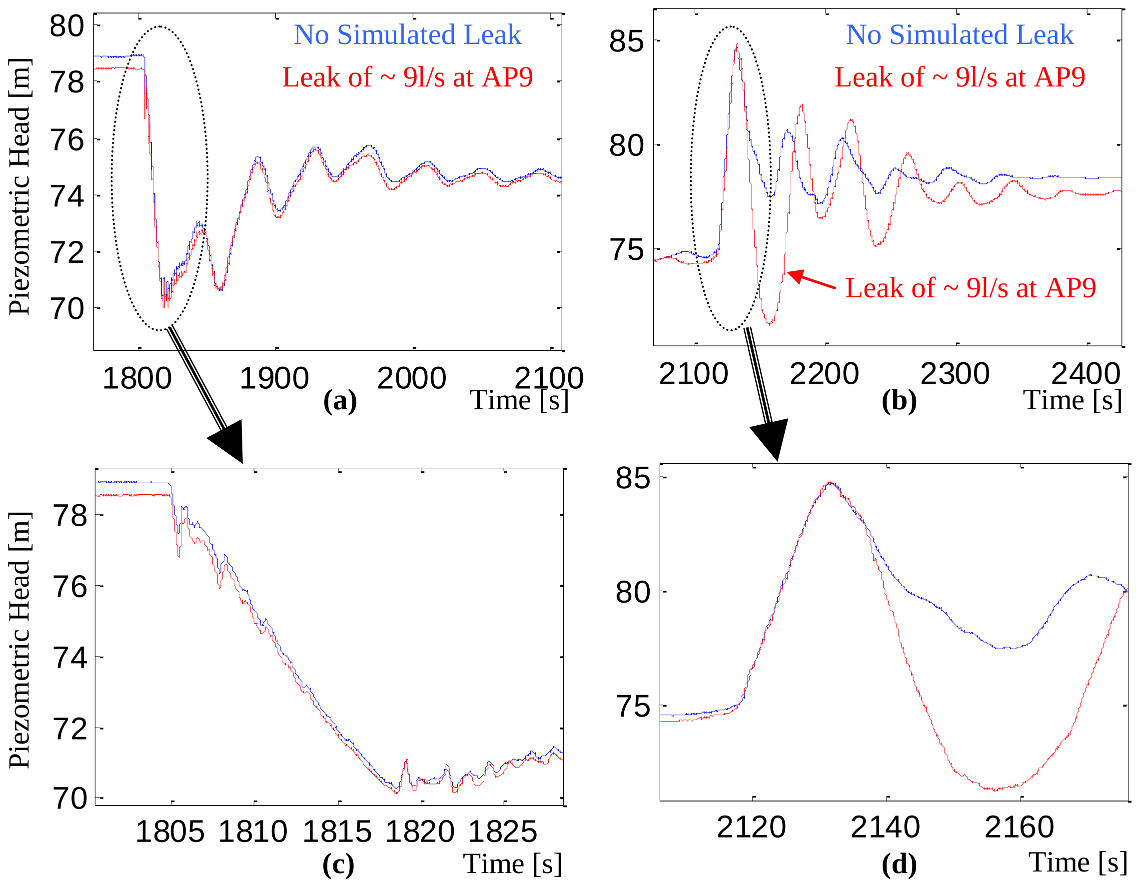

Figure 8. Comparison between no-leak (test3) and leak (test5) cases for switching off/on one pump. Leak with a flow of ~9l/s was simulated at AP 9: (a) pump being switch off; (b) pump being switched on; (c) detail of (a); and, (d) detail of (b).

The simulated leaks were very large but relatively small in comparison to the base flow of ~ 515 l/s to be able to affect the generated transient events. These results well agree with the results from the laboratory experiments carried out by the authors which illustrate that leaks less than 10 to 15 % of the base flow are not detectable using controlled transient events. The problem was further exacerbated by hydraulic noise, reflections due to branches, changes in pipe diameter and the fact that protection devices dampened regular operational changes.

4.2 *Experimental set 2*

The purpose of these experiments was to validate the use of small surge events generated at access points along *Pipeline A* for locating leaks or other features. For that purpose, a step pulse was introduced at AP7 by instantaneously opening and then closing (after 10 minutes) an installed gate valve (Figure 9a). The discharge at AP7 for a fully open 50mm (2”BSP) valve was approximately 22 l/s (Figure 9b). An electrically actuated solenoid valve was installed at AP10 and used for simulating leaks (Figure 9c). Flow and pressure were measured at AP 9 and 11 (IC-DAS) as AP10 was used to generate leaks. In this way, sharp pressure waves with small overpressure (less than 0.5 bar) were generated which did not affect the operational regime of the pipeline

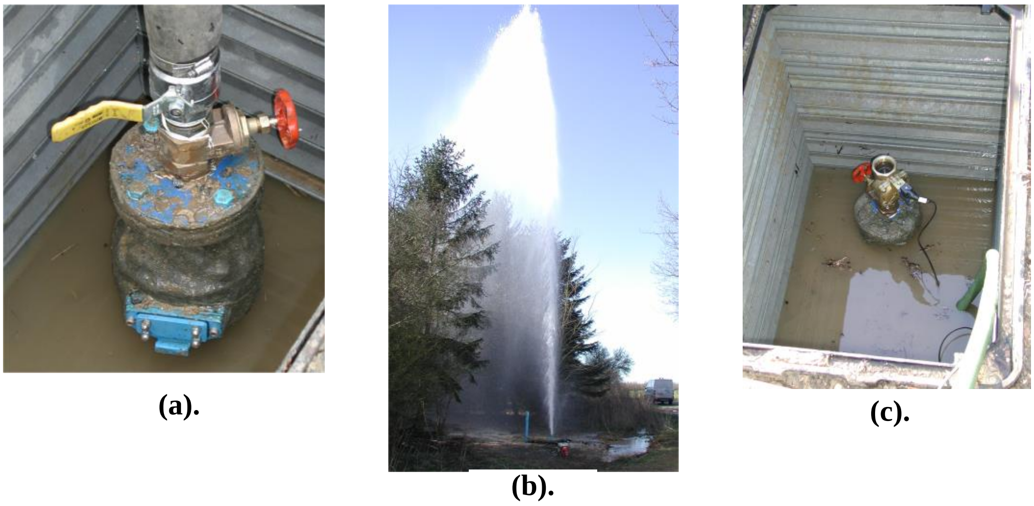

Figure 9. Pulse generation at AP7 and leak at AP10: (a) Ball valve at AP7 used for the instantaneous opening and closure for generating a pressure pulse; (b) Flow discharge at AP7 (~22 l/s); and, (c) Solenoid valve (electrically actuated) at AP10 for simulating leaks. Leak flow ~ 2 l/s.

Figure 10a shows the piezometric head at AP 9 and AP11 for a pressure pulse generated at AP7 with no simulated leaks while Figure 10b shows the same setting with a leak of ~ 2 l/s simulated at AP10.

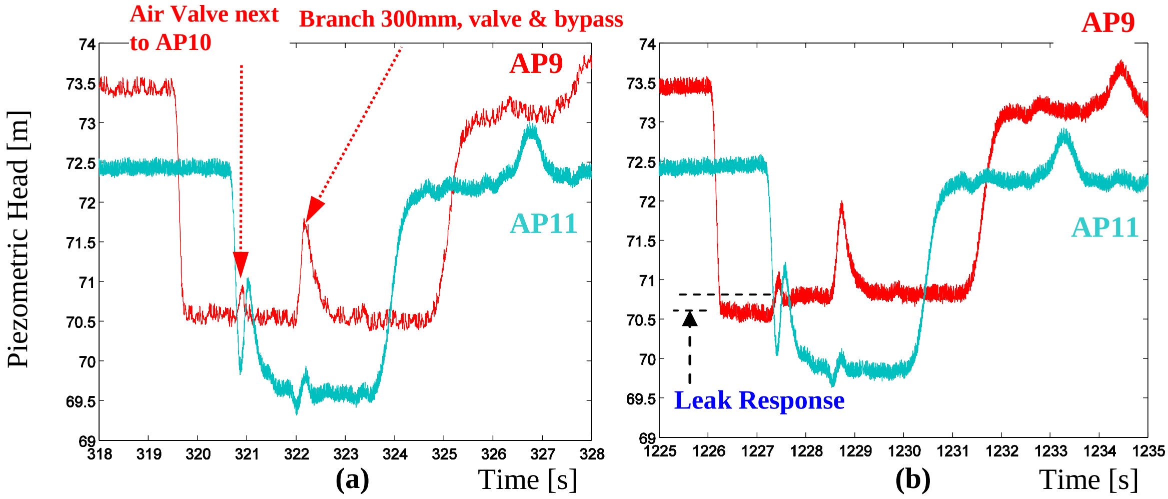

Figure 10. Comparison between a non-leaking and a leaking pipeline for a pressure pulse generated at AP7: (a) piezometric head acquired at AP9 and AP11 for the no-leak case; (b) piezometric head at AP9 and AP11 for the leak case. Leak with an approximate flow of ~2 l/s was simulated at AP10.

Two features can be distinguished at Figure 10a. The first one is caused by the air valve located within 5 m from AP 10, while the second one is junction (~ 15m from AP11) at which several topological changes occur: a branch connection (OD 300mm), a bypass and the diameter of the transmission pipeline changes from 860 mm to 812 mm OD. It is very likely that the slight variation of in the piezometric head after the reflection from the air valve (Figure 10b) is caused by the simulated leak.

5 CONCLUSIONS

This paper presents the results of field tests which have been carried out to validate the application of controlled transient events for detecting and locating leaks in water transmission pipelines. To the best knowledge of the authors, results of similar controlled field trials have never been published before. The tests were carried out using a specifically assembled data acquisition system which allows high frequency (up to 1000 S/s) time-synchronised collection of flow and pressure data. Such a sophisticated data acquisition system has never been used before in acquiring data during transient events in the water industry

A survey of the topological characteristics of 12 operational transmission pipelines from two water utilities in the UK showed that water transmission pipelines are rarely single pipelines rather than branched systems with a number of features which affect the propagation of a pressure pulse much more than a leak. The selected pipeline system for the field tests was a system which can be classified as a typical transmission pipeline.

Two experimental sets were completed at the selected case study.

The results from experimental set 1 show that hydraulic transient events can not be used for detecting and locating reasonably sized leaks. Leaks of ~ 9 l/s (1.8% of the base flow) discharging to atmosphere did not affect the propagation of transients generated during regular operational changes in *Pipeline A*.

The results from experimental set 2 show that instantaneously created pressure pulses might be more successful in detecting and locating leaks. However, it is very unlikely that this technique will have any practical value for the water industry considering the conditions which were required for setting up the experimental tests.

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References

Brunone, B. (1999). "Transient Test-Based Technique for Leak Detection in Outfall Pipes." *Journal of Water Resources Planning and Management*, 125(5), 302-307.

Brunone, B., and Ferrante, M. (2001). "Detecting Leaks in Pressurised Pipes by Means of Transients." *Journal of Hydraulic Research*, 39(5), 539-547.

Covas, D. (2003). "Inverse Transient Analysis for Leak Detection and Calibration of Water Pipe Systems: Modelling Special Dynamic Effects," PhD, Imperial College London.

Covas, D., Almeida, A. B., and Ramos, H. (2000). "Leak Location in Pipe Systems Using Pressure Surges." *Proceedings 8th International Conference on Pressure Surges*, The Hague, The Netherlands.

Graham, N., Maksimovic, C., Stoianov, I., and Covas, D. (2003). "Final Report for Epsrc Grant: Gr/M68213/01: Inverse Transient Analysis in Pipe Networks for Leak Detection, Quantification and Roughness Calibration." Imperial College London.

Jonsson, L. (1995). "Leak Detection in Pipelines Using Hydraulic Transients. Laboratory Measurements." Report. University of Lund. Department of Water Resources Engineering, Sweden.

Jonsson, L. (2001). "Leakage Detection in a Pipeline Based on the Analysis of Hydraulic Transients." *IWA specialised conference: System Approach to Leakage Control and Water Distribution Systems Management*, Brno, Czech Republic, 16-18 May, 81-88.

Kapelan, Z., Savic, D. A., and Walters, G. A. (2000). "Inverse Transient Analysis in Pipe Networks for Leakage Detection and Roughness Calibration." *CWS 2000; Water network modelling for optimal design and management*, Exeter, 143-160.

Liggett, J. A., and Chen, L. C. (1994). "Inverse Transient Analysis in Pipe Networks." *Journal of Hydraulic Engineering*, 120(8), 934.

Mpesha, W., Gassman, S. L., and Chaudhry, M. H. (2001). "Leak Detection in Pipes by Frequency Response Method." *Journal of Hydraulic Engineering*, 127(2), 134-148.
Stoianov, I., Covas, D., Karney, B., Maksimovic, C., and Graham, N. (2002a). "Wavelet Analysis of Synchronised Transient Signals for Leak Location in Pipelines." *Journal of Hydraulic Engineering, ASCE*, Submitted for publication, 1st September, 2002.
Stoianov, I., Karney, B., Covas, D., Maksimovic, C., and Graham, N. (2002b). "Wavelet Processing of Transient Signals for Pipeline Leak Location and Quantification." *Proceedings of 1st Annual Environmental & Water Resources Systems Analysis (EWRSA) Symposium, A.S.C.E. EWRI Annual Conference*, Roanoke, Virginia, US.
Stoianov, I., Maksimovic, C., and Graham, N. (2003). "Designing a Continuous Cost-Effective Leak Detection System for Transmission Pipelines." *International Conference on Advances in Water Supply Management.CCWI-Computing and Control for the Water Industry (15-17 September)*, London, UK.
Tang, K. W., Brunone, B., and Karney, B. (2001). "Role and Characterization of Leaks under Transient Conditions." *International Association of Hydraulic Engineering and Research; Environmental hydraulics and eco hydraulics*, Beijing, 572-577.
Vitkovsky, J. P., Simpson, A. R., and Lambert, M. F. (2000). "Leak Detection and Calibration Using Transients and Genetic Algorithms." *Journal of Water Resources Planning and Management*, 126(4), 262-265.
Vitkovsky, J. P., Simpson, A. R., and Lambert, M. F. (2002). "Minimization Algorithms and Experimental Inverse Transient Leak Detection." *Conference on Water Resources Planning and Management, American Society of Civil Engineers*, Roanoke, Virginia, May 20-23.[CD-ROM].
Wang, X. J., Lambert, M. F., Simpson, A. R., Liggett, J. A., and Vitkovsky, J. P. (2002). "Leak Detection in Pipelines Using the Damping of Fluid Transients." *Journal of Hydraulic Engineering*, 128(7), 697-711.
Wylie, E. B., Streeter, V. L., and Suo, L. (1993). *Fluid Transients in Systems*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.