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Practical Paper

Water pipe system response under dynamic effects

Helena Ramos and Didia Covas

ABSTRACT

Recent developments based on the flow acceleration/deceleration, mechanical responses of the pipe-wall material and leakage are analysed in order to better understand the pipe system response under transient conditions for pressurised flows, in terms of amplitude, phase and shape. These events have been performed by using collect data in transient tests obtained for different pipe system characteristics (two experimental facilities and a real-life system). Current commercial transient solvers cannot accurately predict the head oscillations in pipes with non-elastic rheological pipe-wall behaviour, such as polyethylene PE, whose application in water supply systems has increased during the last years. Experimental procedures are carried out aimed at the collection of data sets of dynamic effects through pressure time variation and flow velocity fields. Pressure transients that naturally occur in pipe systems propagate back and forth in the pipes and carry information about features of the system, such as the presence of a leak, providing a potential tool for leak detection.

Key words | damping effects, dynamic conditions, leak detection, pipe-wall behaviour, water pipe system

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INTRODUCTION

Waterhammer analysis is important in the design of water pipeline systems to select pipe materials, to size wall thickness in order to sustain pressure ratings and to specify surge protection devices. The aim of this research is the presentation of the main dynamic effects in water pipe systems by using physical data collected in three experimental facilities - (i) one developed in the Department of Civil Engineering (DEC) and (ii) in the Department of Mechanical Engineering (DEM), both at Instituto Superior Técnico – IST (Lisbon, Portugal), and (iii) in a real case – Balmashanner trunk main system at Lintrathen East Trunk Main Network of Scottish Water (Dundee, UK). Comparisons between experimental and computational results using the Method of Characteristics (MOC) enhance some special dissipative effects that can be identified as the main sources of pressure wave dissipation and dispersion for different transient conditions.

A well-known problem is the inability to predict the fluid pressure variation along time associated with the pipe velocity fields, in terms of amplitude, phase and shape of the pressure waves, during a transient event. In addition, there is a lack of experimental data for new pipe materials (i.e. PE pipes) to support a physical understanding of how the system behaviour influences the dissipation of energy in observed data.

Available commercial codes usually adopt the quasi-stationary hypothesis when calculating the friction factor during transient flow conditions, assuming at each instant and cross section, the equations deduced for uniform steady-state flows are valid. It has been shown that this assumption does not allow the proper prediction of pressure variations between two steady-state flow regimes.

The one-dimensional (1-D) models are the most popular and they are based on a corrective factor to the

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steady-state friction parameter when a uniform velocity profile is assumed in each pipe section and in each instant. In addition these models have shown to produce good fits to experiments for rigid pipe materials, such as metal and concrete. However, it is fundamental to investigate the physical meaning of this effect, in order to predict the head oscillations in non-elastic materials (in particular PVC, HDPE), whose application for water supply systems has increased during the last years and it is essential for design and diagnosis analysis to detect any type of anomaly, such as the presence of a leak.

A BRIEF BACKGROUND REVIEW

The classical waterhammer models, which assume a linear-elastic behaviour of the pipe-walls and a quasi-steady state friction loss to estimate the head losses along the pipe, have been presented in the literature (Chaudhry 1987; Almeida & Koelle 1992; Wylie & Streeter 1993) and used to predict the maximum and minimum pressure surges in time. However, with the recent increasing implementation of plastic pipes and the occurrence of special dynamic effects, which need advanced calibrated models, the classical formulation is quite imprecise in describing the hydraulic transients regarding the attenuation, the dispersion and the shape of the pressure wave. Some researchers attribute these effects to friction losses of both flow regimes, that is, steady and unsteady-state conditions. Whilst unsteady friction can be reasonably well described for laminar flows (Zielke 1968; Trikha 1975), several formulations for unsteady friction calculation have been presented (e.g. Vardy *et al.* 1993; Vardy & Brown 1995; Brunone *et al.* 1995; Vitkovsky *et al.* 2000; Ramos & Loureiro 2002; Ramos *et al.* 2004), although the numerical results present large discrepancies with experimental data for polyethylene (PE) pipe systems both in terms of the general shape, period and damping of the pressure waves. Although the viscoelastic behaviour of polymers is known, the behaviour is usually forgotten in hydraulic analysis. Rieutford (1982) analysed laminar transient flow in viscoelastic pipes and proposed a one-element Kelvin-Voigt model. For this pipe material there is an instantaneous-elastic response and a retarded-viscoelastic response that can be incorporated into an additional time-dependent term into the mass-balance equation (Rieutford & Blanchard 1979; Covas *et al.* 2004a,b). The necessity of novel methods of detecting and locating leaks led many researchers to investigate transient-based techniques for leak location (Covas & Ramos 1999).

DATA COLLECTION

Transient data were collected at IST – DEC and DEM ((i) and (ii), respectively) laboratory facilities and (iii) in a real gravity system, in order to investigate different responses associated with steady and unsteady friction factors, pipe non-elasticity and leakage occurrence.

Experimental set-up 1

Experimental set-up 1 (Figure 1) is composed of a single transmission pipeline connected to an air vessel with 0.8 m^3 volume at the upstream end, with free discharge to a constant water level tank at the downstream end. The pipe material is a high-density polyethylene (HDPE) NP10, with a total length of 200 m, an inner diameter of 0.043 m, a wall thickness of 0.0035 m, a pipe roughness of 0.00005 m and an elastic wave speed of 280 m/s (Figure 2).

A ball valve is installed at downstream end (pipe section 3 of Figure 1), which is used to interrupt the flow in order to perform a fast closing manoeuvre. The air vessel was used to keep the upstream pressure constant behaving as an elevated reservoir (Figures 1 and 2). The pressure was measured using transducers, with a range of -1 to 9 bar, at pipe section 3 that is close to the downstream end valve, to record the system response. Between sections 1 and 2, there is a transparent PVC pipe to assure that there is no free air inside the pipe.

Experimental set-up 2

Experimental facility 2 (Figure 3) is composed of a single transmission pipeline connected to a pressurised tank at the upstream end (pipe section 1), a constant water level reservoir at the downstream end and a diaphragm valve pneumatically actuated to generate the transient, at the downstream end (pipe section 3). The valve discharges directly to two in-line free surface reservoirs. In this set-up, the pipe is also of a high-density polyethylene (HDPE) NP6,

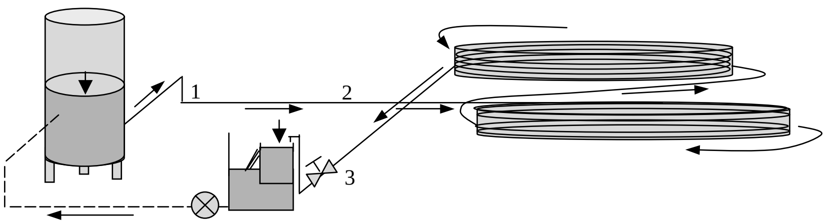

Figure 1 | Scheme of experimental facility 1 with HDPE pipe (L = 200 m).

with 0.05 m of nominal diameter and 0.002 m of wall thickness. The experimental facility includes, in the returned circuit, three centrifugal pumps in parallel and a pressurised tank with 1 m^3 volume, at the upstream end. The length of the pipeline between the pressurised tank and the diaphragm valve is 108 m (Figures 3 and 4), including 8 m of perspex pipe (between pipe sections 2 and 3), where the Particle Image Velocimetry (PIV) technique is used to measure flow velocity fields.

Real-life system

The field case is a real water system composed of a branched transmission pipeline. The tests were carried out in Balmashanner main pipeline, which has 5940 m of length and 0.30 m of diameter of ductile iron. This water main is a gravity system, which supplies a 10,000 m^3 Service Reservoir (TWL of 172 m) and is supplied from Clear Water Tanks at Lintrathen Water Treatment Works (TWL 210.5 m). The normal daily flow is 2000 m^3, with a flow control valve which is restricted to a peak inlet flow of 28 l/s (Figure 5).

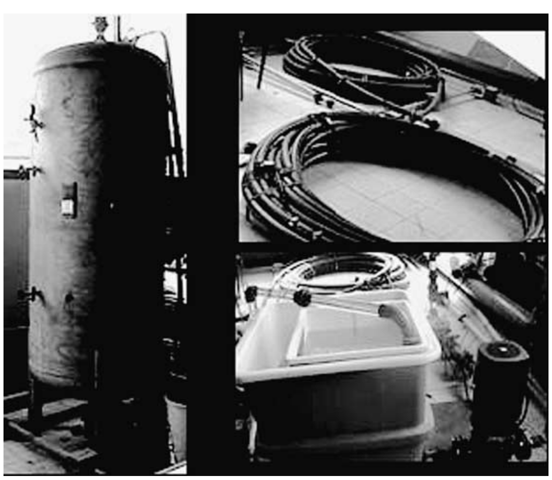

Figure 2 | Details of experimental facility 1: pressurised tank, coils of HDPE pipe and downstream tank.

ANALYSIS OF RESULTS

Frictional and mechanical effects

In experimental facilities 1 and 2, a large number of data sets were collected with a sampling rate of 100 Hz. In the field case of Scottish Water, the sampling rate was 20 Hz.

In set-up 1, these tests covered a wide range of flows (Figure 6) (Ramos & Loureiro 2002; Loureiro & Ramos 2003).

One of the main factors which contribute to the dissipative effects of pressure waves is the continuous head losses along the pipe (Ramos 1995; Ramos *et al.* 2004) due to the friction and turbulence effects. The estimation of the extreme up-surge can be obtained by Frizell-Joukowksy formulation, $\Delta H_J = cV/g$. As a result of the influence of head losses, the piezometric head can increase, and this phenomenon is known as the line-packing effect visible in the first pressure peak, as well as the pressure dissipation during the wave propagation. The line-packing effect can be estimated by

$$\Delta H \approx \frac{J_s L}{\Delta H_J} - \frac{1}{6}\left(\frac{J_s L}{\Delta H_J}\right)^3 \qquad (1)$$

This equation is a parabolic approximation of this phenomenon, in accordance with the detail presented in Figure 6b. The correct prediction of the pressure wave propagation, in particular the effect of the pipe wall viscoelasticity, is not always properly accounted for (Vardy & Brown 1995; Ramos *et al.* 2004; Covas *et al.*

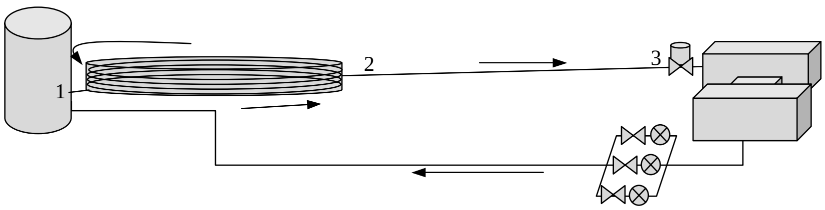

Figure 3 | Scheme of experimental facility 2 with HDPE pipe (L = 108 m).

2004b, 2005). This effect influences the system operation rules, advanced model calibration and the dynamic behaviour of each system type. Transient solvers commercially available in the market are not suitable for predicting the pressure surge which is observed in real systems (Ramos 2003; Ramos *et al.* 2004).

A new simplified approach of the surge is presented taking into account the pressure peak in time:

$$H = H_f \pm K_1 Q_o D_e \tag{2}$$

where H_f = the final steady state piezometric head which separates the upsurge from downsurge in a symmetric way, if the upstream boundary condition is a reservoir; and K_1 = coefficient related to the Joukowsky overpressure.

This can be a combined effect of the non-elastic behaviour of the pipe-wall and unsteady friction presented in detail in Ramos *et al.* (2004). This approach aims at the characterisation of energy dissipation through the variation of the extreme piezometric heads in time (Figure 7).

In a rigid (or low deformable) pipe with an elastic response type (e.g. metal or concrete pipes), the damping energy effect (D_e) for rough turbulent flows can be obtained according to the following equation:

$$D_e = \frac{1}{1 + K_2 t} \tag{3}$$

In a plastic pipe, with a non-elastic response type (e.g. PVC, HDPE), the pipe wall retarded behaviour is the main factor responsible for the pressure dissipation (Ramos *et al.* 2004; Covas *et al.* 2004b, 2005) which can be adequately described as follows:

$$D_e = e^{-K_2 t} \tag{4}$$

with (K_2 t) the attenuation factor between two consecutive pressure peaks, which depends on the pipe length, pipe material, pipe roughness and inertial effects.

The classical equations that describe one-dimensional transient flow in pressurised pipe systems are (Wylie &

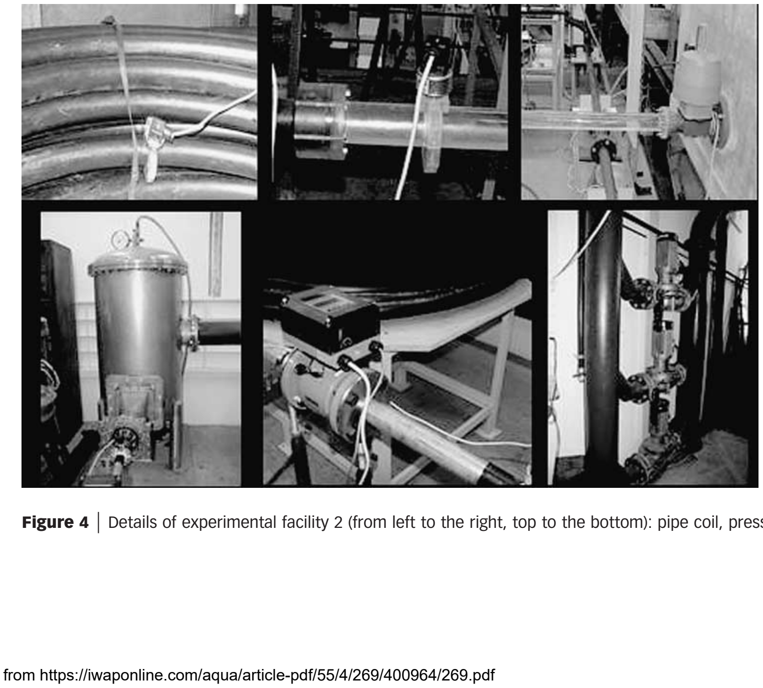

Figure 4 | Details of experimental facility 2 (from left to the right, top to the bottom): pipe coil, pressure transducer, diaphragm valve, air vessel, flow meter and pumps.

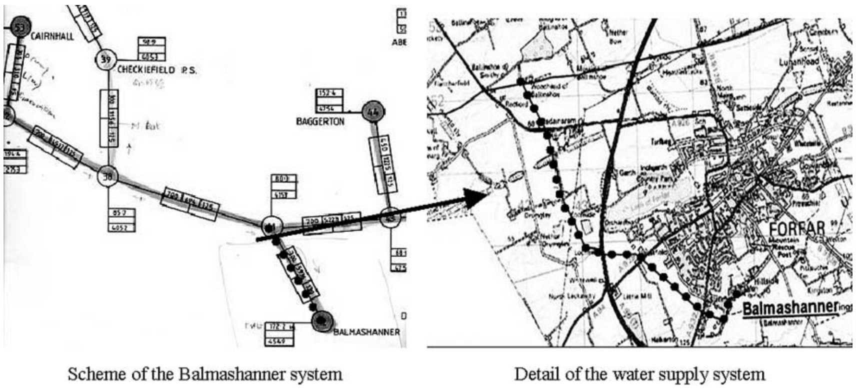

Figure 5 | Balmashanner system at Lintrathen East Trunk Main Network (line with dots).

Streeter 1993):

$$\frac{dH}{dt}+\frac{c^2}{gS}\frac{\partial Q}{\partial x}=0 \quad (5)$$

$$\frac{\partial H}{\partial x}+\frac{1}{gS}\frac{dQ}{dt}+J=0 \quad (6)$$

in which Q = flow-rate (m^3/s); H = piezometric-head (m); c = elastic wave speed (m/s); g = gravity acceleration (m/s^2); S = pipe cross-section (m^2); x = coordinate along the pipeline axis (m); t = time (s); J = gradient energy line (m/m).

Several assumptions are made in the derivation of these equations, the most important being: the unsteady-state friction losses which are calculated similarly to steady-state; the rheological behaviour of the pipe material which is assumed linear-elastic; and the pipe is uniform and completely constrained from any axial or lateral movement. In order to account for unsteady-state friction losses, the hydraulic headloss gradient J is decomposed into two terms: a steady-state component (J_s) and an unsteady-state component (J_u), $J = J_s + J_u$. The steady-state component is easily obtained by adequate formulation depending on the type of the flow regime (i.e. laminar or turbulent). The unsteady component is usually neglected in the classic waterhammer solution. However, rapid transient events require a more appropriate representation of this effect. Trikha formulation was used in this work (Figure 8). In an attempt to distinguish the viscoelastic effect of the pipe-wall from the unsteady-friction effect, the model was calibrated for the laminar conditions (Re = 1300) considering unsteady friction effects. Though not accurate, Trikha's formulation can be considered a good approximation of Zielke's exact formula for laminar conditions:

$$J_u \approx \frac{16\nu}{gD^2}[Y_1+Y_2+Y_3] \quad (7)$$

with $Y_i(t)=Y_i(t-\Delta t)e^{-n_i\frac{4\nu}{D^2}\Delta t}+m_i[V(t)-V(t-\Delta t)]$, the parameters n_i and m_i are null before the transient starts, and $m_1=40$, $n_1=-8000$, $m_2=8.1$, $n_2=-200$, $m_3=1$ and $n_3=-26.4$, during the transient.

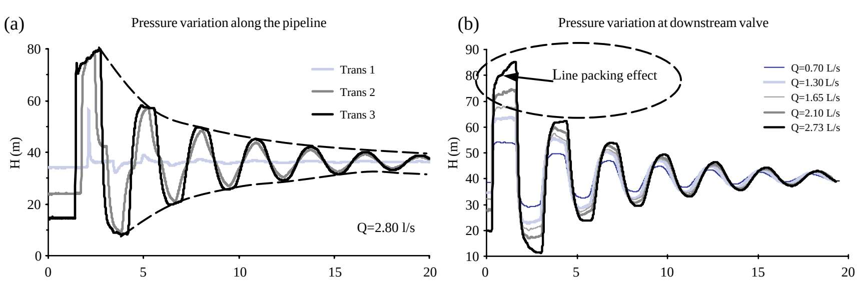

Figure 6 | Experimental tests in facility 1: a) pressure variation along the pipe (for different positions of transducers); b) pressure variation at the valve for different discharge values.

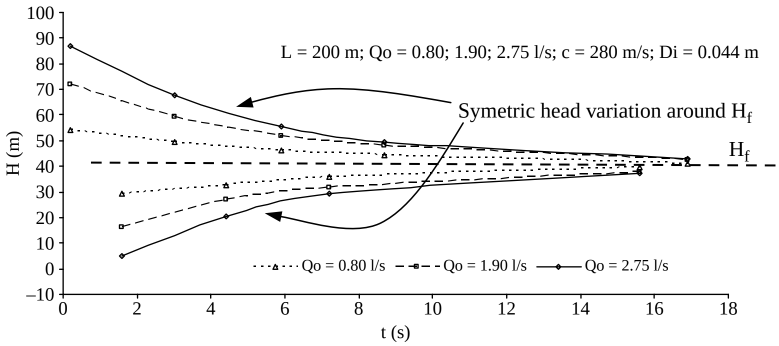

Figure 7 | Effect in a plastic pipe due to viscoelasticity and friction.

A novel formulation (Ramos & Loureiro 2002; Loureiro & Ramos 2003; Ramos *et al.* 2004) based on Brunone *et al.* (1991) formula which was also modified by Vitkovsky *et al.* (2000) has shown to be more adequate for turbulent flows, though it relies on two empirical coefficients K_{qt} and K_{qx}, which have to be calibrated based on collected data for each system characteristics:

$$J_u = \frac{1}{gS}\left(K_{qt}\frac{\partial Q}{\partial t} + K_{qx}\, c\,SGN(Q)\left|\frac{\partial Q}{\partial x}\right|\right) \quad (8)$$

It has been numerically verified that the term K_{qt} affects the phase shift of transient pressure waves and K_{qx} affects the damping effect and both are associated with the local and convective acceleration (Figure 8).

According to Figure 9 it can be seen that the proposed formulation enables a better fit to the experimental results when compared to the Vitkovsky *et al.*'s formulation. The coefficient K_{qt}, associated to the local acceleration of equation influences the head oscillations essentially in terms of phase. Coefficients K_{qt} and K_{qx} have been estimated by trial and error. This analysis has shown that these parameters are practically constant for different Reynolds number, defining the limits of K_{qx} for Kv variation through the formula proposed by (Vardy & Brown 1995):

$$K_v = 2\sqrt{\frac{7.41}{Re^{\log(14.3/Re^{0.05})}}} \quad (9)$$

The numerical pressure wave propagates faster than the experimental wave for smaller values of K_{qt} and tends to be slightly delayed compared to the observed wave for higher values. Based on experimental tests it was verified that K_{qt} varied [0.004;0.0054] and K_{qx} [0.033;0.05], for the system analysed with the original length (L = 200 m) and with

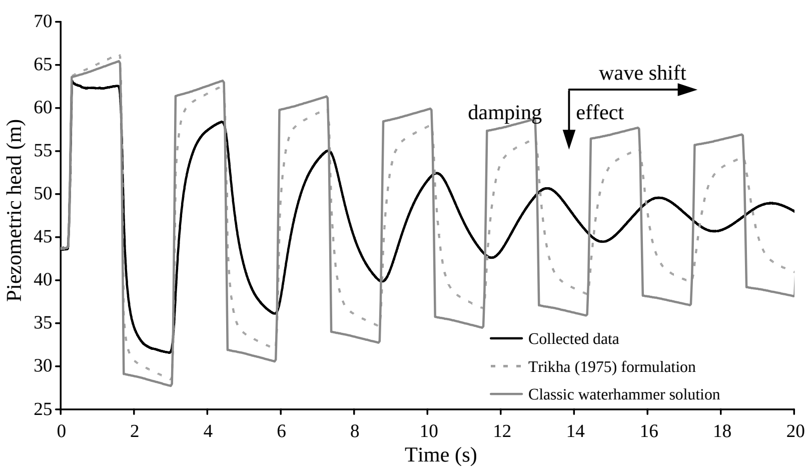

Figure 8 | Effect and wave dispersion in a plastic pipe due to viscoelasticity and friction influence.

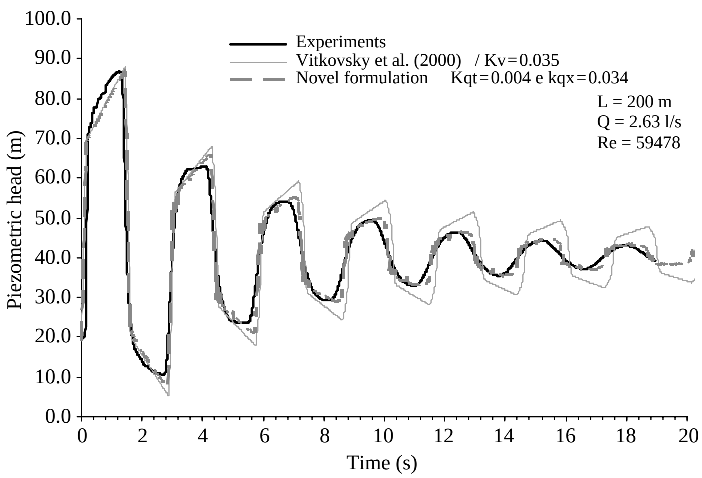

Figure 9 | Comparisons between experiments and transient roughness models.

L = 100 m. The analysis allows concluding that the coefficient K_{qx} is much more dependent on the pipeline head losses (i.e. dependent on its length) than K_{qt}, as it attains higher values for smaller head losses, with $K_{qt} \approx 10\% \ K_{qx}$.

With this novel approach, it is possible to reproduce reasonably well the experimental observations in terms of pressure and phase (Figure 9). However, the shape of the pressure wave propagation is much sharper than the real one. For long pipelines with metal or concrete pipe wall and high steady state flow discharge, where the packing effect is very important, the results fit quite well with the pressure peaks at the valve section.

In order to better understand friction and turbulence effects during fast transient events, velocity fields were obtained in a transparent pipe section located 2 m from the downstream end valve in Set-up 2, using a Particle Image Velocimetry (PIV) technique (Figures 10 and 11).

The PIV technique is an experimental measure-technique which allows characterising instantaneous velocity fields in a pipe section. It is an optical method without inducing any flow disturbance, where the flow velocity is estimated based on the flow velocity of particles. These particles must be focused by a laser light plan at least twice for the same time interval. The velocity is obtained based on the movement of recorded images.

The assessment of the velocity field results, for some time intervals after the rapid pneumatic valve closure, is associated with the temporal evolution of the pressure wave (see detail of

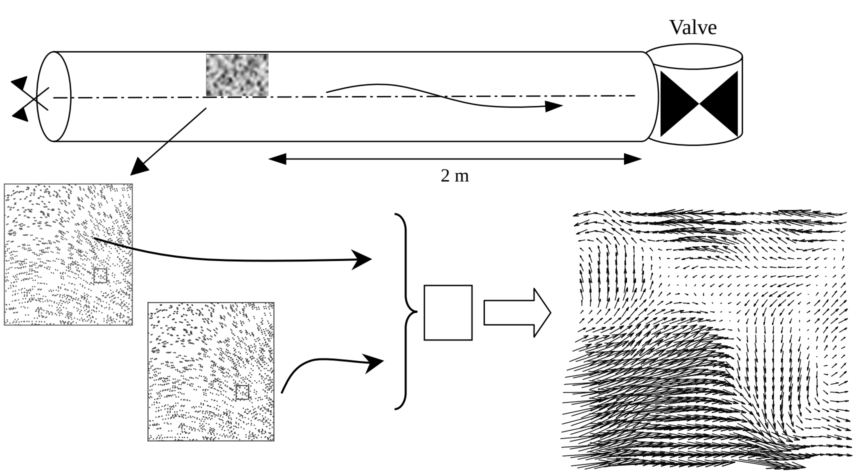

Figure 10 | Application of the PIV technique in a perspex pipe of experimental facility 2 for field velocities achievement (Hacamo 2002).

the pressure first elevation at the bottom in Figure 11). The analysis of these velocity fields and the velocity profile allows the following remarks (Figures 11 and 12):

(i) the pressure gradient induces a rapid reduction of the mean flow velocity;
(ii) the flow deceleration is more significant near to the pipe wall since it is there that the flow inversion occurs first;
(iii) when the flow inversion occurs (i.e., in this case $t \sim 0.630$ s), the time instant corresponds to the inflexion point of the time pressure evolution;
(iv) after the flow inversion is visible, vortexes form which originate a velocity field with a practically null spatial mean velocity;
(v) in less than $t \sim 2L/c$, the inside flow is almost stopped and the unsteady friction effect can be neglected.

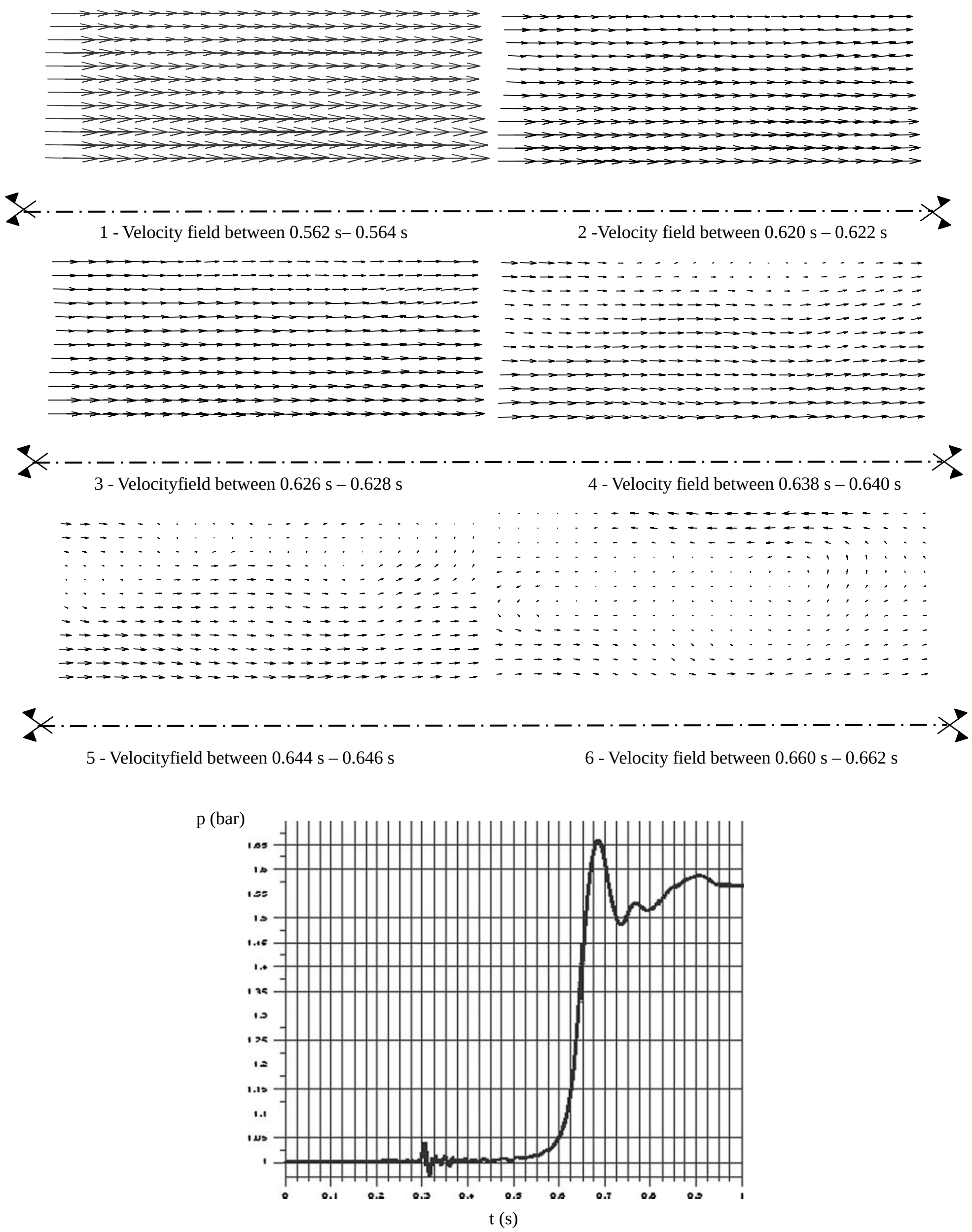

Figure 11 | Velocity fields for set-up 2 during the up-surge (Hacamo 2002).

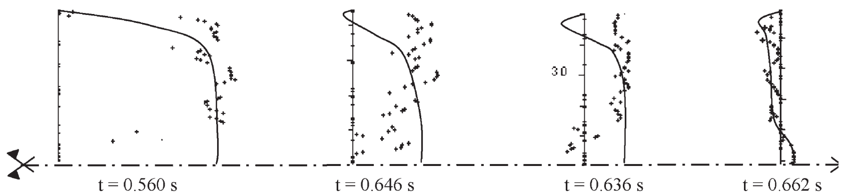

Figure 12 | Velocity profiles (for half pipe section).

As referred the classic waterhammer analysis assumes linear-elastic behaviour of the pipe-walls and a quasi-steady state friction-loss which are commonly used for design purposes. These assumptions, however, are not fully verified in hydraulic transients generated by rapid changes in flow conditions. Whilst unsteady-friction losses are prevalent in metal and concrete pipes, non-linear elastic behaviour of pipe-walls is significant in plastic pipes and it cannot be ignored. Since the most advanced unsteady formulations cannot fit well enough with the attenuation and the wave dispersive effects along time period specially for plastic pipes, where the friction effect can be almost neglected, the rheological pipe material behaviour i.e. the viscoelasticity, is certainly the most significant effect influencing the dissipative effects of the pressure waves (Ramos *et al.* 2004; Covas *et al.* 2004b, 2005). This effect is well observed in Figure 13, where experimental tests are compared with different numerical simulations obtained by the classic theory of waterhammer, Trikha's and Brunone's friction formulations and a viscoelastic solver which presents a very fitness with the collection data (Covas *et al.* 2004b, 2005).

These effects have required continuous and recent developments in parameterisation regarding model calibration, essentially for diagnosis analysis of existent systems, as well as for leak detection by using transient solvers.

Leakage effect

Leakage is another effect which can influence the pressure variation. Regarding the presence of a leak in pipe systems, a sudden effect appears due to the flow discharge induced by the pressure wave propagation in the leak position, since the leak has a typical orifice response (Figure 14) (Covas & Ramos 1999; Covas *et al.* 2000; Covas *et al.* 2004a), having a similar behaviour as a relief valve (Ramos 1995). Taking into account that the percolation in the porous soil is very low and the flow kinetic energy at the outside of the leak can be neglected, the flow discharge for a small leak, in a buried pipe, is a function of the difference between the total energy flow inside the pipe and the piezometric head at the outside, as well as on the dimension and shape of the orifice.

The discharge law is of the following type:

$$Q_L = C_v A \sqrt{2g\left(\frac{p_i}{\gamma} - \frac{p_e}{\gamma}\right)} \quad (10)$$

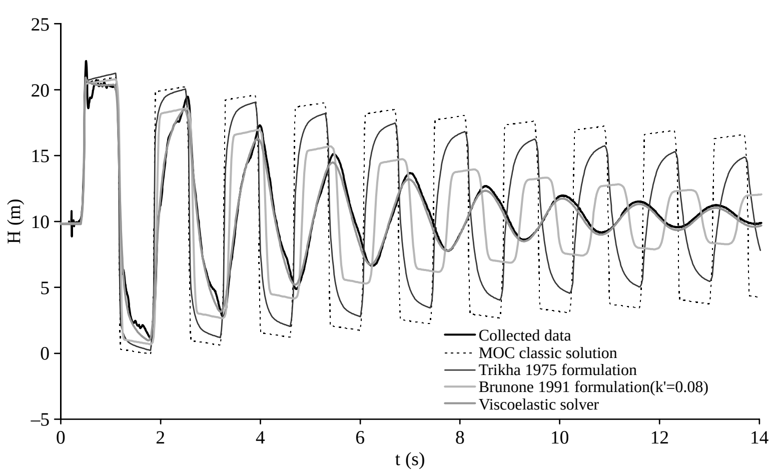

Figure 13 | Piezometric head at the downstream end of experimental facility 2: transient data vs numerical simulations.

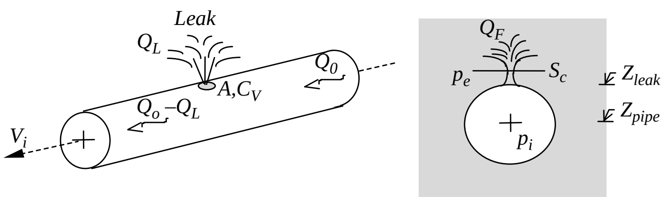

Figure 14 | Schematic presentation of a leak. Physical fundamental parameters.

in which Q_L = leak discharge (m^3/s); C_v = discharge orifice coefficient (−); A = the orifice section (m^2); p_i and p_e = pressures inside and outside the pipe, respectively.

In the derivation of this equation, the difference of geometric levels between the axis of the pipe and the orifice can be neglected. In this way the leak discharge depends only on the difference between the pressure inside and outside the pipe and also on the physical characteristic of the orifice. Usually, it is considered that the value of the kinetic energy inside the pipe can be neglected for average velocities ($V \leq 1\,m/s$) and normal operation pressures of water supply networks, i.e. $10\,m \leq p/\gamma \leq 60\,m$. The leak effect using the information carried in a transient pressure signal seems particularly useful for single pipes.

When a pressure surge is induced in a pipeline, every singularity of the system, such as a branching junction or a reservoir, a valve partially opened, reflects pressure waves that interfere with the common shape of the hydraulic transient. A leak is not an exception and, undoubtedly, it reflects induced pressure surges. Thus, the main objective is to analyse the reflected wave produced by a leak in order to detect, locate and quantify its discharge.

Consider a hydraulic system composed of an up-stream constant water level reservoir, a conduit with a downstream valve, in which the fluid is flowing with the velocity V_o and the initial steady state pressure at the valve is H_o. Any instantaneous change in the valve setting at the time instance t_o would induce a velocity and a pressure variation of ΔV and ΔH, respectively, at the valve section. It is well known that these instantaneous variations are correlated by the universal Frizell-Joukowsky formula ($\Delta H_J = cV/g$). In the case of the singularity being a leak (Figure 15), it reflects a wave that induces a sudden upsurge in the valve section. Due to downstream valve closure, the pressure surge starts to propagate along the pipe, part of the incident wave is dissipated, part is reflected backward (ΔH_r) and another part is transmitted forward (ΔH_t). Neglecting energy losses along the pipe, the reflected wave added to the transmitted wave equals the incident wave (ΔH).

For fast manoeuvres of total valve closure (e.g. starting with different initial discharge values), the location of the leak might be estimated by the total time taken by the incident wave to arrive at the leak to be reflected and to arrive back at the valve again, $t*$. The distance of the leak from the valve, X, is determined by

$$X = \frac{ct^*}{2} \tag{11}$$

in which c stands for the pressure wave speed. If the closure time T is greater than time $t*$, it might not be possible to identify, in the shape of the transient pressure at the valve, the time instant of arrival of the first reflected wave, $t*$.

Concerning the magnitude of the leak, quantified, for instance, by the relative leak flow $Q_{Lo}/(Q_o\text{-}Q_{Lo})$, in which Q_o is the steady state flow upstream of the leak and Q_{Lo} the leak flow (see Figure 15), it might be estimated by the amplitude of the reflected wave.

In order that the leak reflects a pressure wave, it is necessary the discharge of the leak undergoes a variation. If the discharge of a leak was insensitive to the pressure variation during the transient regime, there would be no reflection, and it would be impossible to determine the

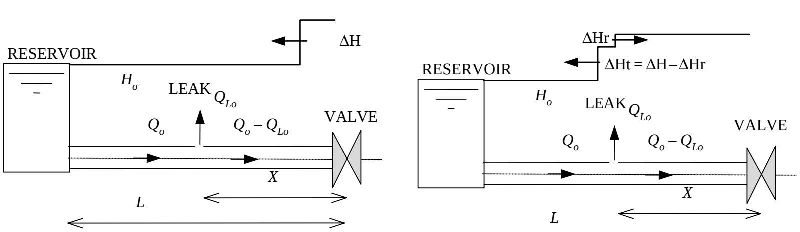

Figure 15 | Topology of the system. Pressure surge generated by a leak.

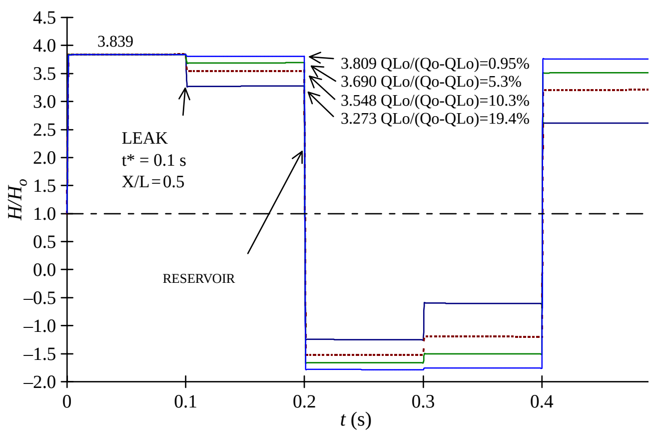

Figure 16 | Pressure surge generated by an instantaneous total valve closure in a simple hydraulic system with a leak at the middle of the pipeline obtained by MOC.

location of the leak, either using time or frequency analysis. Since the discharge of the leak varies like an orifice with a constant opening degree, it induces a reflected pressure surge, ΔH_r. The leak reflected wave ΔH_r, as it reaches the closed valve, incurs a total reflection. Hence, the sudden ΔH_d observed in the pressure shape next to the valve is double the leak reflected wave ($\Delta H_r = \Delta H_d/2$) and is related to flows Q_0 and Q_{L0} by the following equation:

$$\frac{Q_{L0}}{(Q_0 - Q_{L0})} = \frac{\Delta H_d}{\Delta H}\left[1 - \sqrt{1 + \frac{\Delta H + \frac{\Delta H_d}{2}}{H_0}}\right]^{-1} \quad (12)$$

This expression was developed based on the equations C^+ and C^- of the Method of Characteristics, considering the leak is at the node next to the valve and that there is no energy dissipation between the leak and the valve.

It is presented in Figure 16 a theoretical example of a pressure surge at the valve section for an instantaneous total valve closure manoeuvre and for the magnitude of several leaks (relative leak flows $Q_{L0}/(Q_0\text{-}Q_{L0})$ equal to 1, 6, 11 and 21%), with the leak located at half distance of the pipe ($X = 0.5\,L$, in which L is the length of the pipeline).

The observed relative $\Delta H_d/\Delta H$ in the pressure surge at the valve section allows the location of the leak and the estimation of the leak's discharge. It should be noticed that there is a difference between the estimated leak flow and real leak flow, even in numerical simulation, although the relative error is less than 5%. This fact is due to the transient head-loss being neglected in the deduction of Equation (12) and it is very important that the greater the distance of the leak from the valve, the smaller the leak reflection. For instance, the smallest leak has a real relative discharge of 1.00% and the estimated one is 0.95% (5% error), while the greatest leak has a real relative discharge of 21% and the estimate is 19.4% (3% error).

This technique is quite sensible to data pressure logger location, the type of closure manoeuvre, the type of pipe material and the diameter of the main pipe, as well the dimensions of the leak, its location, the presence of air or other singularities in the pipe system.

In the practical application, transient data collected at Balmashanner trunk main with a simulated leak by a fire hydrant was used to test the travelling wave technique, in a real system. In this case, the system is a metal pipe with an

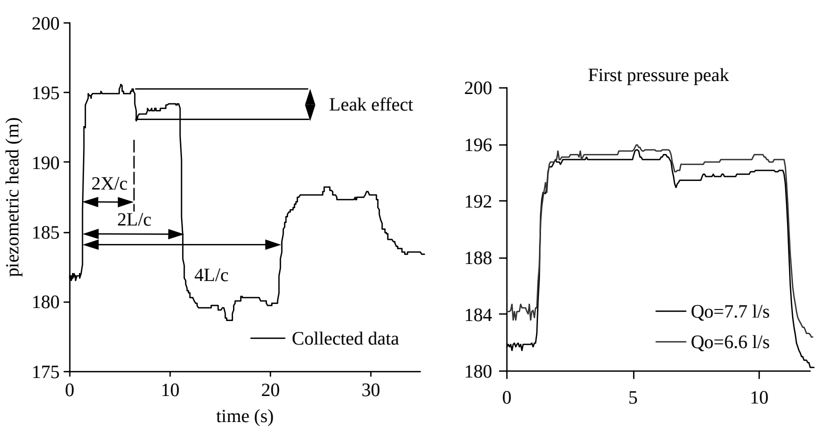

Figure 17 | Lintrathen East Trunk Main Network (Balmashanner). Leak effect in the piezometric head variation due to a fast downstream valve closure.

Table 1 | Leak location by travelling wave principle

Ho (m)	28.1	26.0
ΔH_{max} (m)	11.5	13.2
Q_o-Q_{Lo} (l/s)	6.6	7.7
X (m)	3101	3176

inner diameter of 0.30 m and the leak influence is quite visible. A selected set of data corresponding to one leak location and two sizes was used. The wave speed was estimated based on the pressure wave period which is $c = 4L/T$ being L = pipe length (m); c = wave speed (m/s); and T = wave period (s) (Figure 17).

Assuming the wave speed ($c \sim 1185$ ms) which is within the range of expected value for the elastic wave speed of ductile iron (~1,100 to 1,200 m/s), the leak location X can be estimated by Equation(11), based on the time analysis of the first peak of the pressure wave and the respective pressure drop induced by the leak (Figure 17). For other parameters must be obtained such as the initial and maximum pressures (Ho and ΔH_{max}) and downstream flow-rates estimated by Frizell-Joukowsky formula.

Regarding results obtained in Table 1, the leak location from the downstream end of the pipe (downstream valve section) varies between 3,101 and 3,176 for the leak position, which is ~1% accurate over the total length of the pipe.

Special care was considered for the amplitude of surges (i.e. less than 14 m) for an average steady state pressure of ~28 m. It shows that it is not necessary to generate high surges, though it requires the use of well controlled (at a pipe end) and fast closure manoeuvres, for example, starting from a quasi-closed valve opening position.

CONCLUSIONS

The main conclusions of these analyses can be summarized as follows:

(i) a model only based on the basic equations of MOC considering the stationary head loss to simulate the dissipative effects cannot describe adequately the system response, in particular in plastic pipes, however, this can be used for the estimation of extreme pressure peaks;

(ii) a model based on MOC which incorporates unsteady friction formulation gives reasonable results for metal pipes, and can be used with some confidence for specification of operational rules;

(iii) two different corrective coefficients (K_{qt} and K_{qx}) associated with the local and convective acceleration in the unsteady friction formulation, Equation(8), have been analysed. It was shown that the use of these two coefficients, instead of a single one, improves the fitting between the results of the numerical simulations and the experimental measurements. The term K_{qt} affects the wave phase and the term K_{qx} affects the surge damping, being always, for the analysed systems, $K_{qt} < K_{qx}$ (i.e. $K_{qt} \approx 10\%\ K_{qx}$);

(iv) it was experimentally verified for both set-up 1 and 2 (made of plastic pipes) that the viscoelasticity of the pipe material significantly influences the pressure wave dissipation as well as the time-propagation;

(v) the leak induces a sudden pressure drop in the first pressure waves and acts as a relief valve increasing the dissipation of transient events. The analysis of the first reflected wave from the leak is numerically an efficient method for leak detection, location and size quantification.

SYMBOLOGY

c : elastic wave speed;
D : pipe diameter;
D_e : damping energy effect;
g : gravity acceleration;
H : piezometric-head;
H_f : the final steady state piezometric head;
Ho : initial head;
J : unit head loss coefficient;
J_s : steady-state unit head loss;
J_u : unsteady-state unit head loss;
K_1 : coefficient related to the Joukowsky overpressure;
K_2 : coefficient;
Kv : decay coefficient of Vardy and Brown formulation;
K_{qt} : decay coefficient which affects the local acceleration;

K_{qx} : decay coefficient that affects the convective acceleration;
L : pipe length;
Q : flow discharge;
Re : Reynolds number;
S : pipe cross-section area;
t : time;
V : flow velocity;
x : coordinate along the pipeline axis;
Yi : Trikha's formulation coefficient (i = 1, 2 and 3);
ΔH : head losses;
ΔHr : reflected wave;
ΔHt : transmitted wave;
ΔH_J : Joukowsky overpressure;
ν : fluid viscosity.

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