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Hydraulic Structures

Shahid Chamran University

Waterhammer tests in a long PVC pipeline with short steel end sections

1. A. Bergant
Litostroj Power d.o.o., Litrostrojska 50, 1000 Ljubljana, Slovenia. E-mail: anton.bergant@litostrojpower.eu

2. Q. Hou
School of Computer Science and Technology, Tianjin University, Tianjin, China. E-mail: qhou@tju.edu.cn

3. A. Keramat
Engineering Department, Jundi Shapur University of Technology, Dezful, Iran. E-mail: a.keramat@jsu.ac.ir

4. A. S. Tijsseling
Department of Mathematics and Computer Science, Eindhoven University of Technology, The Netherlands. E-mail: a.s.tijsseling@tue.nl

Abstract

An experiment featuring waterhammer in viscoelastic pipes is presented in which the effects of pipe-wall viscoelasticity on waterhammer pressures are investigated. A large-scale pipeline apparatus made of polyvinyl chloride (PVC) at Deltares, Delft, The Netherlands, has been used to carry out waterhammer experiments. Tests have been conducted in a reservoir-pipeline-valve system consisting of a main viscoelastic pipeline and two short steel pipes placed upstream and downstream of the main pipe. Rapid closure of a manually operated valve at the downstream end generates waterhammer. Repeated measurements at several positions along the pipeline have been recorded; these are plotted in figures and interpreted.

Keywords: *Waterhammer*, *Viscoelasticity*, *PVC*, *Pipe*, *Experiment.*

1 Introduction

The application of pipes made of viscoelastic materials has much increased in recent years, making it necessary to do more theoretical and experimental research on their mechanical behaviour when placed in hydraulic systems. Here, a large-scale pipeline apparatus at Deltares, Delft, The Netherlands has been used as a test system providing data for the validation of mathematical and numerical models for predicting the waterhammer response in plastic pipes. The main part of the system under consideration is a horizontal 235.4 mm inner-diameter PVC pipe of 261.2 m length with control valves at the downstream and upstream ends. At nine locations along the pipeline, including a supply steel pipeline and an outlet steel pipeline, transient pressures were measured. The recorded data were analysed and, as it was expected, they show a considerable damping mainly due to the rheological behaviour of the pipe wall. The collected data of this experiment have also been used to validate the mathematical model and the numerical results of Bergant et al. (2011). There it was shown that the incorporation of both unsteady skin friction and viscoelastic pipe wall behaviour in the hydraulic transient model contributed to a more favourable fitting between numerical results and observed data. Viscoelastic materials show a retarded deformation in addition to the immediate response which is normally observed in elastic media. The viscoelastic circumferential strain of the pipe wall is theoretically taken into account by a convolution integral which is based on pressure history and pipe material creep properties. The viscoelastic strains affect the fluid flow continuity equation and introduce an additional term compared to the standard formulation of waterhammer. This issue causes the pressure wave speed to be a time-dependent factor. Covas et al. (2004a, b, 2005) investigated the pressure decay of transient flow in viscoelastic pipes, for which they gave a mathematical model and its numerical solution. Incorporation of retarded strains in the mathematical model introduced a significant damping in the results, which was in accordance with their observations. The model was then extended to include other transient effects such as column separation (Keramat et al. 2010) and fluid-structure interaction (Keramat et al. 2012). Brunone et al. (2000) and Brunone and Berni (2010) studied the significance of the unsteady pipe friction effect and its interaction with viscoelasticity. Unsteady friction and pipe wall viscoelasticity have similar effects on the transient pressures. Soares et al. (2008) and Duan et al. (2010) argued that the combination of the two mechanisms must contribute to an accurate calculation of the damping of pressure waves. This issue was also discussed by Bergant et al. (2008a, b), who, besides the damping effects of viscoelasticity and unsteady friction, investigated other effects such as gaseous cavitation, fluid-structure interaction, leakage and blockage.

The coefficients of the creep functions describing viscoelastic materials are usually determined by inverse transient analysis (ITA) based on collected transient pressure data (Covas et al 2005). This is done by solving

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

an optimization problem, which determines the coefficients such that the transient solver gives results as close as possible to the experimental data (tuning). The difficulty in this procedure is that the creep coefficients are very sensitive to the collected transient data. This is because in the ITA the material properties, which are actually related to the pipeline walls, are evaluated using hydraulic data instead of structural data, or instead of using direct mechanical tests on a specimen of the wall material. This introduces a significant uncertainty in the obtained creep coefficients. However, the use of the ITA in finding the creep data is almost inevitable, because separate material tests are expensive and do not give the desired results. Some influential effects, such as axial and circumferential constraints of the pipeline, confining soils in the case of buried pipes, temperature dependencies, past-time histories, and fluid radial inertia effects are usually not simulated, so that the ITA incorporates them in the calibrated creep coefficients. In this view, an experimental facility for collecting the pressure signals as precise as possible is an important asset at which the current work is aiming.

Waterhammer in viscoelastic pipes has been experimentally investigated by several researchers such as Covas et al. (2004a, b, 2005), who conducted tests on a 277 m high density polyethylene (HDPE) pipeline known as Imperial College test, Soares et al. (2008), who reported tests on a 203.2 m polyvinyl chloride (PVC) pipeline conducted at São Carlos School of Engineering, Brazil, and Güney (1983) who conducted tests in a 43.1 m low density polyethylene (LDPE) pipe referred to as Lyon experiment.

The current research concerns a main viscoelastic pipe with short steel pipes upstream and downstream. The steel sections distinguish it from previous experimental and numerical works in this field. Detailed information regarding the apparatus and instruments is provided. It can be used for constructing future experimental waterhammer facilities. It allows for closely investigating the system by means of existing mathematical models. The pressures measured at several locations are presented in clear figures, thus providing a good source of data for making comparisons with numerical calculations of waterhammer. The experimental data show no signs of occurrence of cavitation and there is favourable repeatability. In addition, they are preferred for the purpose of creep function calibration compared to previous experiments (Covas et al 2004a, b 2005; Soares et al. 2008). The preference is because of a constant head tank being the upstream boundary condition (instead of a pressurized air vessel utilized in the two aforementioned tests), causing the upstream head not to change significantly during the transient tests. As a result, in the present ITA procedure the creep characteristics are not affected by the upstream head variation, which was conjectured to be the case in previous experiments.

2 Methodology

Rheological behaviour of viscoelastic pipe walls causes much damping in waterhammer pressures. This behaviour is generated by retarded circumferential strains which occur with some delay with respect to the pressure fluctuations. This delay is related to the important feature of viscoelastic materials that there is a lag between their immediate and ultimate (static) response in particular to a sudden constant loading (see Fig. 1-left). In rheology, this property is captured by creep and relaxation tests on specimens. Creep compliance indicates how the strain ε increases with time under a step stress σ_0 as $\varepsilon(t) = J(t)\ \sigma_0$. Several models have been suggested to simulate this time-dependency thus providing the constitutive stress-strain relation. Among them the generalized Kelvin-Voigt model (Fig. 1-right) proved to be more appropriate for viscoelastic solids. Its creep compliance function is

$$J(t) = J_0 + \sum_{k=1}^{N_{KV}} J_k \left(1 - e^{-t/\tau_k}\right), \qquad (1)$$

where t is time and J_0, J_k, τ_k and N_{KV} are constants. From a physical viewpoint, it implies that the viscoelastic material resembles a system of springs and dashpots arranged as shown in Fig. 1-right. In this view the parameters in $J(t)$ are: $J_0=1/E_0$ where E_0 is the modulus of elasticity representing the immediate response of the material (Hook's law), J_k defined by $J_k=1/E_k$ is the creep compliance (and E_k is the modulus of elasticity) of the k-th spring, and $\tau_k = \mu_k/E_k$ is the retardation time (and μ_k is the viscosity) of the k-th dashpot (Wineman and Rajagopal 2000).

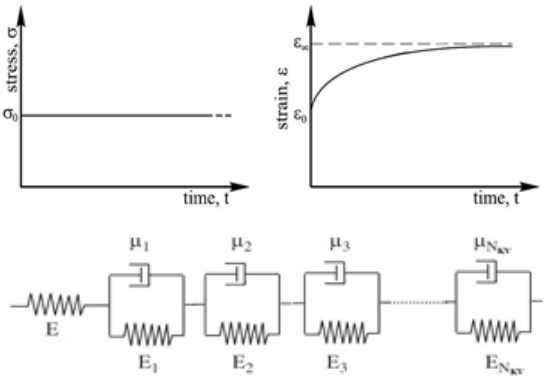


Fig 1. Top: creep test on a viscoelastic specimen; Bottom: generalized Kelvin-Voigt model (Brinson and Brinson 2008).

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

The governing equations of waterhammer in viscoelastic pipes are the conventional waterhammer equations (Wylie et al. 1993) with an additional term in the continuity equation accounting for the retarded strain (Covas et al. 2005; Keramat et al. 2012).

3 Pipe apparatus and instrumentation

The test rig used in the experiments (Deltares HydrolabIII-Delft-4) has been described in detail by Laanearu et al. (2009, 2012) and by Bergant et al. (2010, 2011). It consists of a water-supply tower of 25 m head, a pressurized air tank, PVC pipes with an inner diameter of 235.4 mm and a basement reservoir (see test rig operation scheme and geometry in Fig. 2). The PVC pipeline was connected to the water tower and the pressurized air tank by steel pipe sections. The water supply into the PVC pipeline was regulated by an inlet control valve (automatically operated butterfly valve) at position x = –29.9 m (Fig. 3). The PVC pipeline outlet was connected to the short outlet steel pipeline with a hand-operated control valve at its downstream end. The PVC pipeline consisted of six straight pipes that are connected by four 90 degree elbows and one horizontal combined 180 degree bend (Figs. 3 and 4). The PVC pipeline was fixed to the concrete floor by regular metal anchors and supported with wooden bricks to reduce sagging. In the upstream part of the PVC pipeline a pipe bridge elevated 1.3 m above the pipeline axis was supported by a tube-frame; the rest of the PVC pipeline was horizontal (Fig 5). The water was supplied through a supply steel pipeline and PVC pipe bridge to the PVC pipe test section for controlled rapid filling of the test section and for water hammer tests (see Fig. 2). In these experimental runs the compressed-air supply piping system was uncoupled from the supply steel pipeline by an undamped swing-type check valve that prevented backflow of water into the air supply line. The 15.9 m long DN200 pipe section between the Y-junction and the check valve was carefully deaerated before each water hammer test. The compressed-air pipeline provided the air plug for a controlled rapid emptying of the PVC pipe test section.

The hydraulic grade line (HGL) along the pipeline was measured by ten pressure transducers located at distances measured relative to the inflow into the horizontal PVC pipeline (at x = 0 m) of –29.9 m (p_{uv}), –14.0 m (p_u), 1.6 m (p_1), 46.6 m (p_3; two pressure transducers), 111.7 m (p_5), 183.7 m (p_7), 206.8 m (p_8), 252.7 m (p_9) and 269.5 m (p_{dv}) (see Fig. 3). The valve generating the waterhammer event was placed at 271.3 m downstream from the horizontal PVC pipe section inlet.

All transducers were of strain-gauge type with a resonance frequency above 10 kHz. The accuracy of all transducers is 0.1% of max range. They all have been installed flush-mounted as good as possible and the transduction principle is the integrated silicon strain-gauge bridge. Five different types of pressure transducers have been used with the details given in Table 1.

Table 1. Specifications of the pressure transducers.

Pressure-transducer label	p_{uv}	$p_{3,top}$, $p_{3,bottom}$	p_u	p_1, p_9	p_5, p_7, p_8, p_{dv}
Type: PDCR	930	4010	4010	4030	4030
Purchase year	1997	2005	2006	2007	2008
Pressure range (bar)	3.5	5	5	7	5

The measured length of the steel supply pipeline connecting the reservoir to the PVC pipeline inlet was L_1 = 20.6 m and the steel pipeline connecting the PVC pipeline outlet to the downstream valve was L_2 = 10.4 m; the total length of the PVC pipeline including inlet section and pipe bridge was L = 275.2 m. The inner diameter of the steel pipes was 206 mm and of the PVC pipeline it was 235.4 mm. The PVC and steel pipe-wall thickness were 7.3 mm and 5.9 mm, respectively. The pipe system specifications are summarized in Table 2.

It was attempted to restrain the pipe system as much as possible to suppress fluid-structure interaction (FSI) effects (Wiggert and Tijsseling 2001). However, it was hard to fix the most downstream free bend leading to the vertical outlet pipe. At this point a heavy mass was attached with a rope to reduce vertical movements (axial movement was restrained by anchors and supports). This is depicted in Figs. 6 and 7.

In each waterhammer test, the ten pressure transducers located at nine different axial positions collected data at a sampling rate of 1000 Hz. The most downstream pressure transducer - the recordings of which are shown herein - was installed in the outlet steel pipeline, 8.3 m downstream from the PVC pipeline outlet and 1.8 m upstream of the connecting 1-inch pipe with ball valve that was used to induce waterhammer. In Fig. 6-left the red arrows show the position of this pressure transducer and the 1 inch ball valve. All pressure transducers, except the upstream-end one (p_{uv}) and the downstream-end one (p_{dv}), were installed on the PVC pipe at the same elevation (z = 0 m). The four experiments were run with the same initial steady discharge of Q_0 = 7 l/s.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

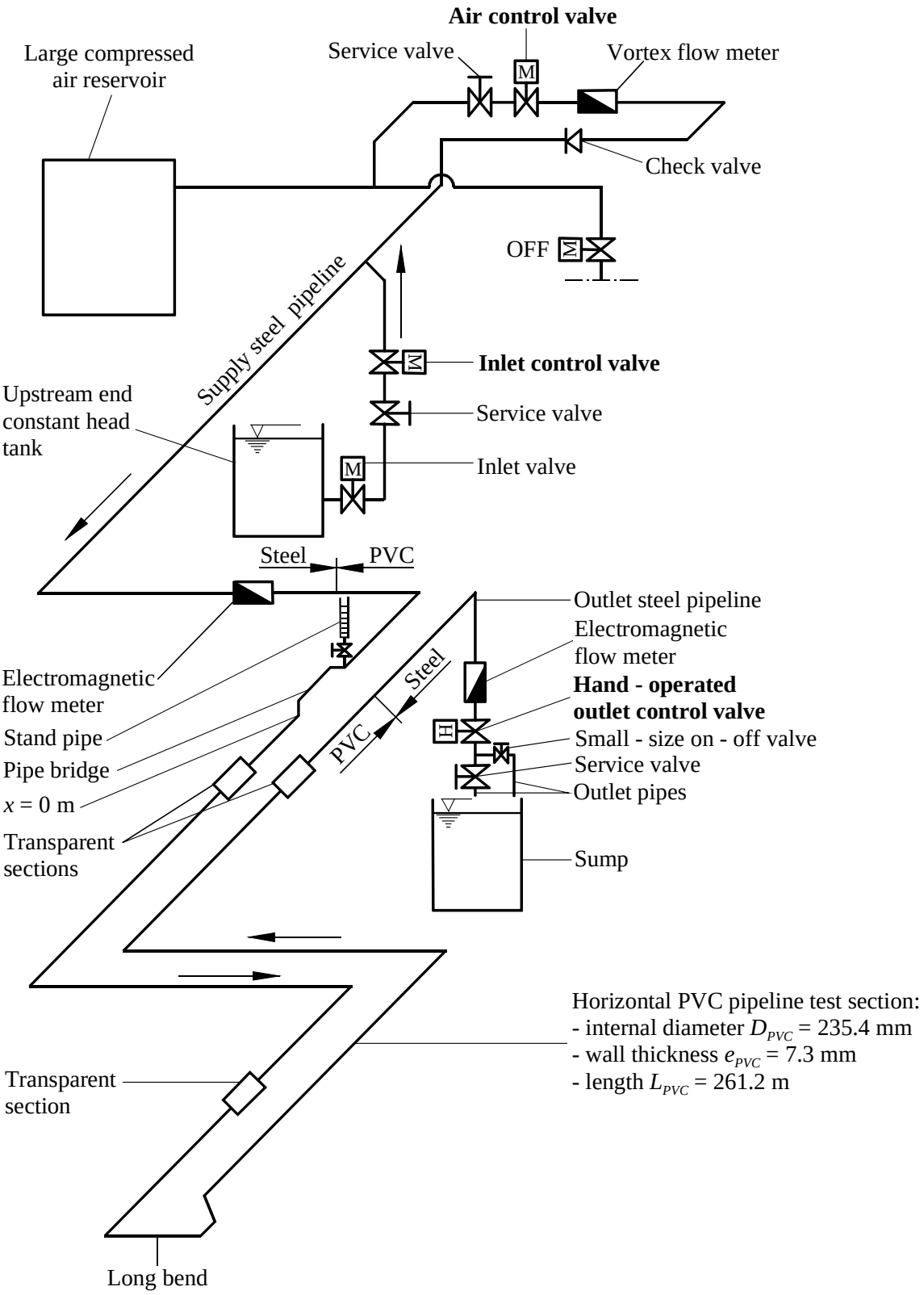


Fig 2. Layout of pipe system apparatus for waterhammer tests.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

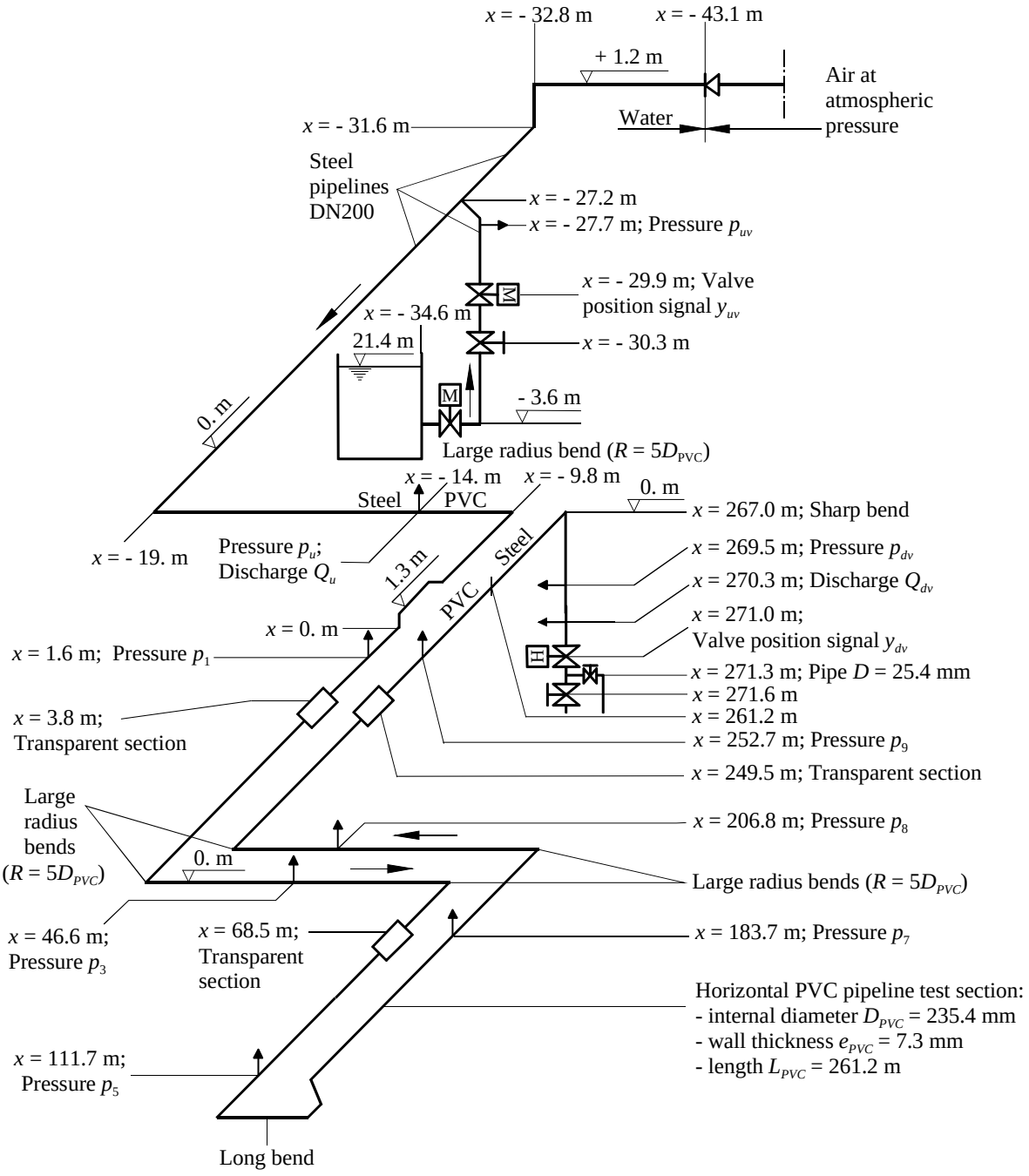


Fig 3. Test rig instrumentation scheme.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University



Fig 4. The PVC pipe 180° turn section and the metal anchors (see the labelled long bend in Figs. 2 and 3).



Fig 5. The PVC pipe bridge, its tube-frame support and pressure transducer p_1 (see red arrow).

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

Table 2. Specifications of the PVC pipeline

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PVC pipe length	Inner diameter of PVC pipe	Length of upstream steel pipe	Length of downstream steel pipe	Inner diameter of steel pipes	Young's modulus (PVC)	Young's modulus (steel)
275.2 m	235.4 mm	20.6 m	10.4 m	206 mm	2.9 GPa	210 GPa

Wall thickness of PVC pipe	Wall thickness of steel pipe	Time of valve closure	Steady state flow rate
7.3 mm	5.9 mm	0.2 s	7 l/s

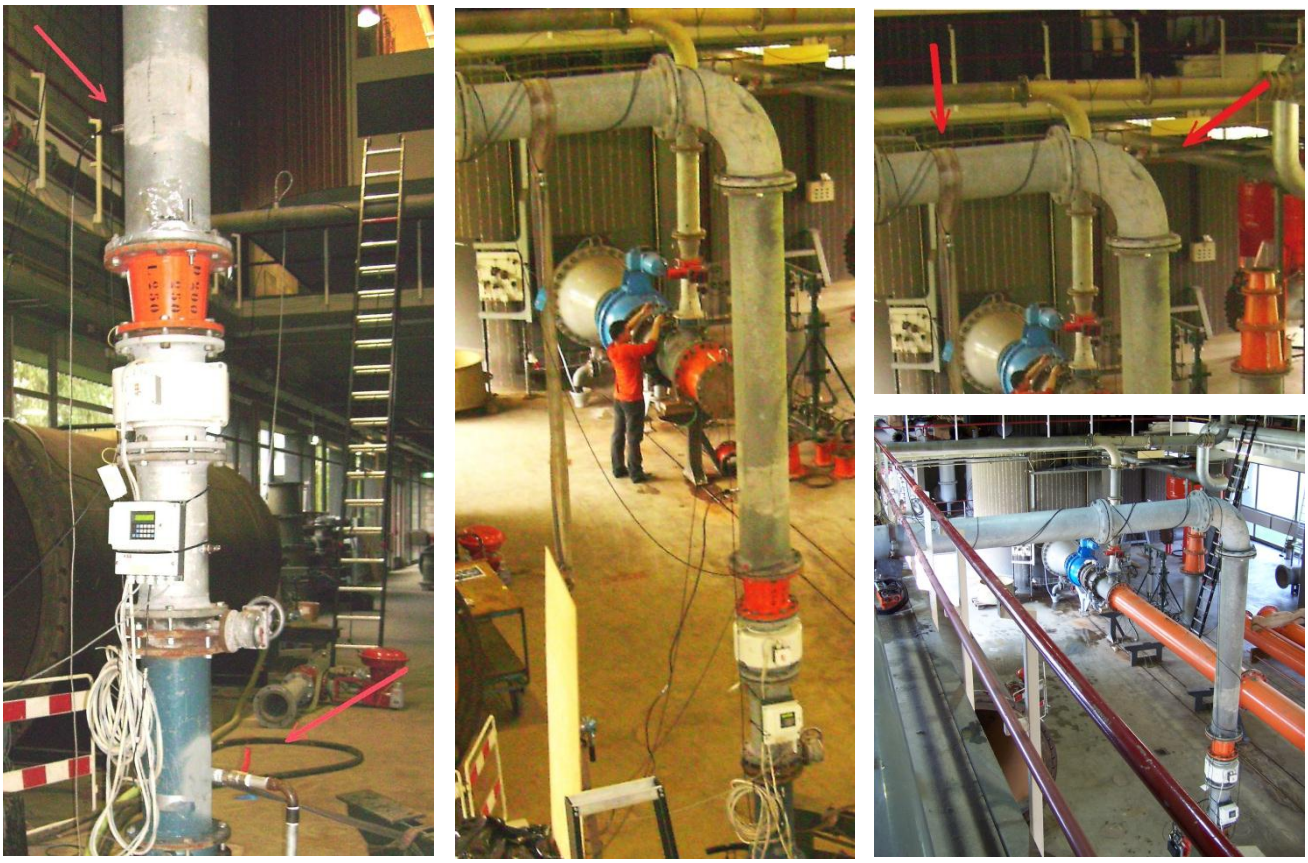


Fig 6. Left: the most downstream pressure transducer and the manually operated valve (indicated by red arrows); middle: downstream steel elbow subjected to FSI effects and the attached heavy mass; top-right: magnification of the middle figure (red arrows show the steel bend and the point where the heavy load was attached); bottom-right: another view of the steel elbow.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University



Fig 7. Two other views of the manually operated valve and the heavy mass (see the red arrows).

4 Experimental results and discussion

To make the measured data of the waterhammer tests comparable, they are shifted in time such that the pressure rise at the *valve* is at t = 0 s. They are also shifted up or down such that the reservoir head remains when the transient flow died out (it occurs after several minutes from the transient flow initiation). The pressure adjustment was necessary because the pressure transducers have false constant shifts in their measurements caused by possible aging and pre-straining of the gauges.

The pressures measured 1.8 m from the valve for two repeated experiments are depicted in Fig 8. Two magnified views are shown in Fig 9. Figures 10 and 11 show the measured pressures at sections 5 and 1 (Fig 3). Similarly, Fig 12 shows pressure signals at the indicated transducers. At section 3, there were two pressure transducers, one on the top and the other on the bottom of the pipe wall and as one might expect, the results were practically identical (not shown here).

As Figs. 8-11 show, the repeatability of the two experiments is good. The minor discrepancy between the traces can be genuinely associated with changed conditions such as: temperature, cumulative creep damage of polymers and support conditions. Viscoelasticity is strongly temperature-dependent, so a little temperature change between the experiments can bring about different results. Degradation of materials due to frequent loadings (fatigue) (Brinson and Brinson 2008) as well as other parameters such as time of the valve closure (as it was closed manually) or a slight movement of axial or circumferential supports can also be the reason for this discrepancy.

The large pressure peak at t = 0 in Figs. 8 and 9 is because the valve closure takes place in a steel pipe. In steel pipes the Joukowsky's pressure head is larger than in PVC pipes due to their larger wave speed.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

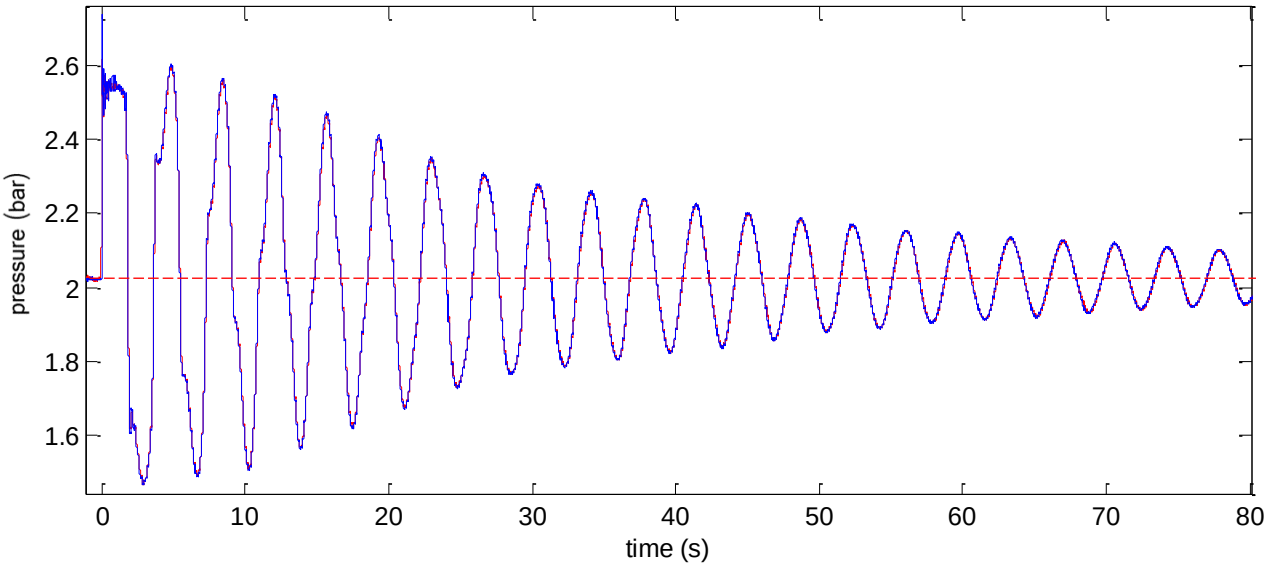


Fig 8. Pressure p_{dv} measured by the transducer close to the downstream valve for two repeated experiments.

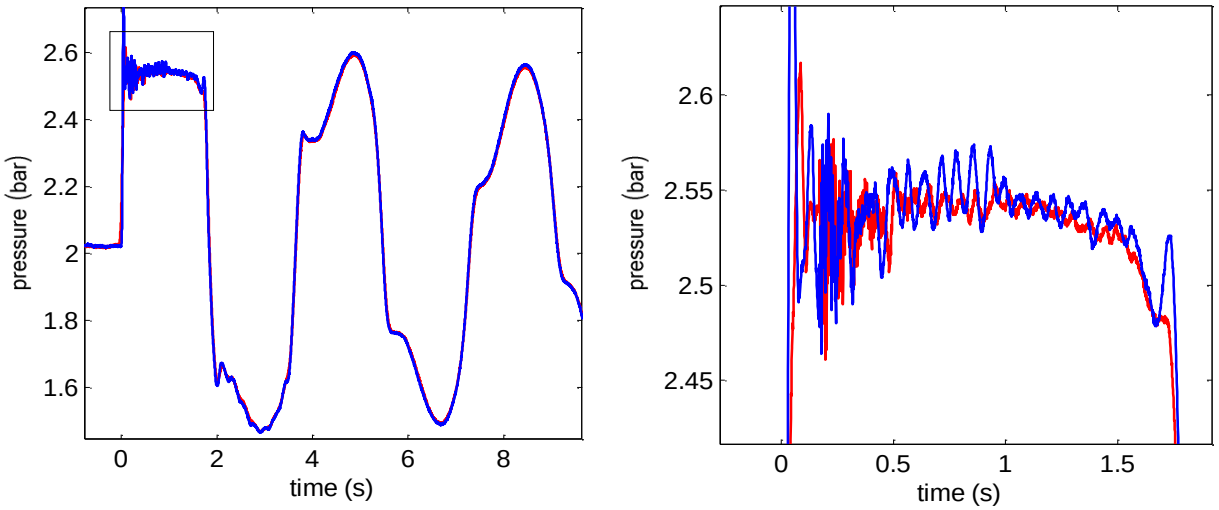


Fig 9. Magnifications of Fig 8.

According to the classical waterhammer theory, following instantaneous valve closure, the Joukowsky pressure of the steel pipe enters (and reflects) at PVC pipe prevails in the first half-cycle. In viscoelastic models, due to the hoop stress, the pipe wall gradually develops the creep behaviour as shown in Fig. 1. It causes to increase the pipe volume at the location at which the high pressure exists. This gradually brings about a small pressure decrease with a concave-up shape in the first half period as demonstrated by researches in the past (Covas et al. 2004a, b, 2005; Güney 1983; Keramat et al. 2012; Achouyab and Bahrar 2011). Friction may also introduce small changes in the curvature of the first half waterhammer cycle, but its effect is small in our case. The aforementioned concave-up profile is not seen in the present experiments and

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

oppositely, a convex-down form for this part is observed (Figs. 8 and 9). This is more or less in accordance with the experimental results reported by Soares at al. (2008). The reason is a slightly different behaviour of PVC pipes.

The other profound effect seen in the Figs. 8 and 9 is that the first main pressure maximum (at $t \approx 1$ s) is slightly lower than the second main one (at $t \approx 5$ s). This does not happen in conventional reservoir-single pipe-valve systems unless effects such as the influence of the short upstream and downstream steel pipes or FSI are taken into account.

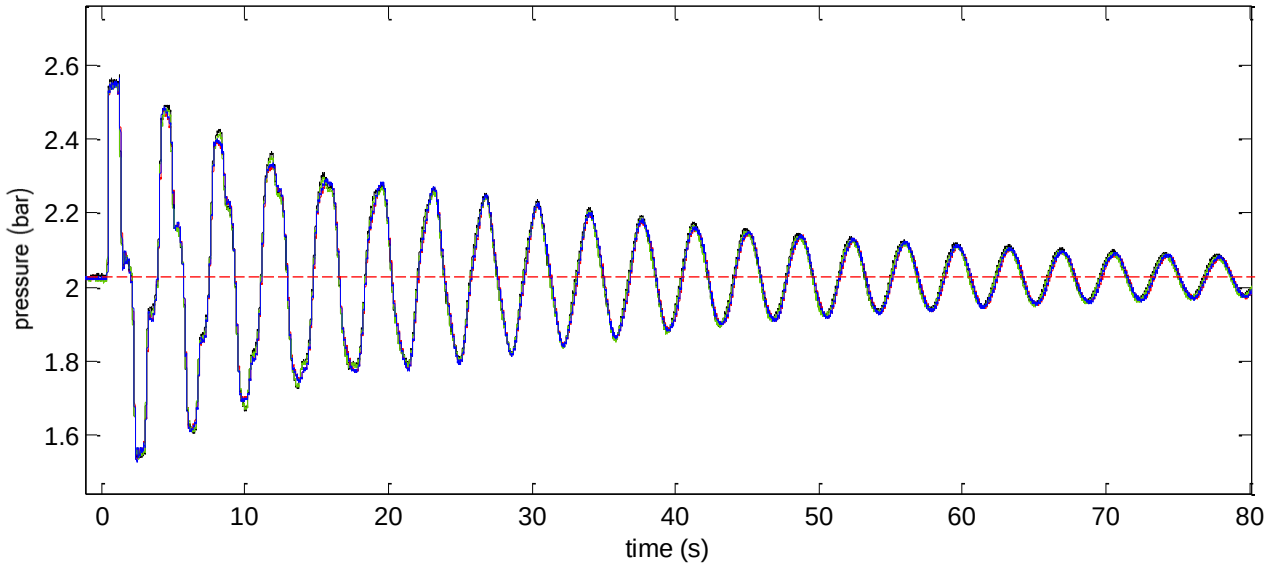


Fig 10. Pressure measured by transducer p_5 located at point 5 for four repeated experiments.

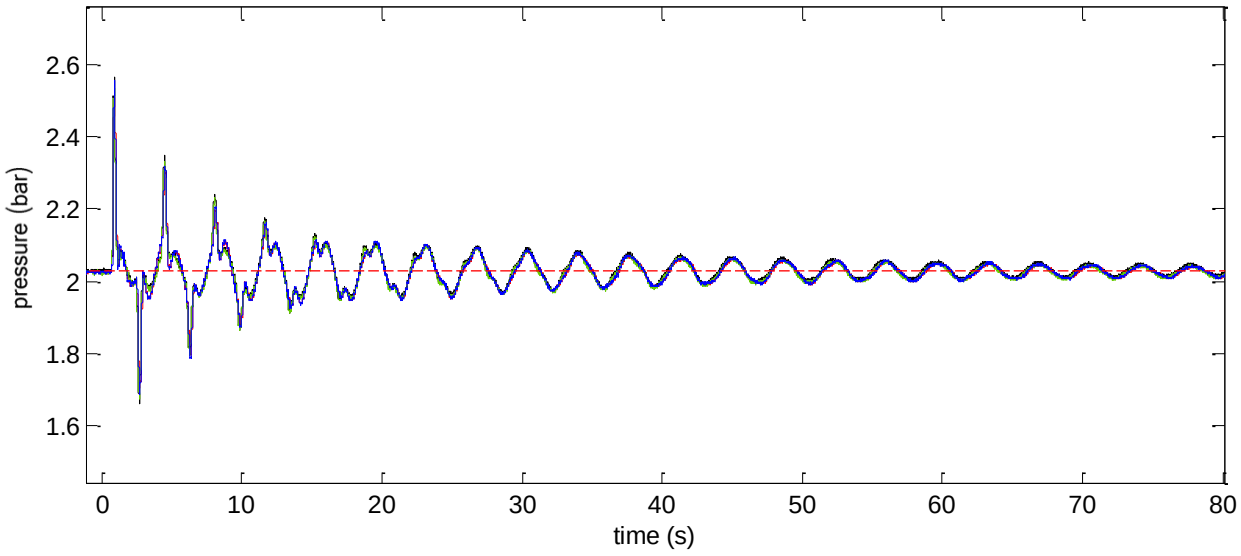


Fig 11. Pressure measured by transducer p_1 located at point 1 for four repeated experiments.

Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

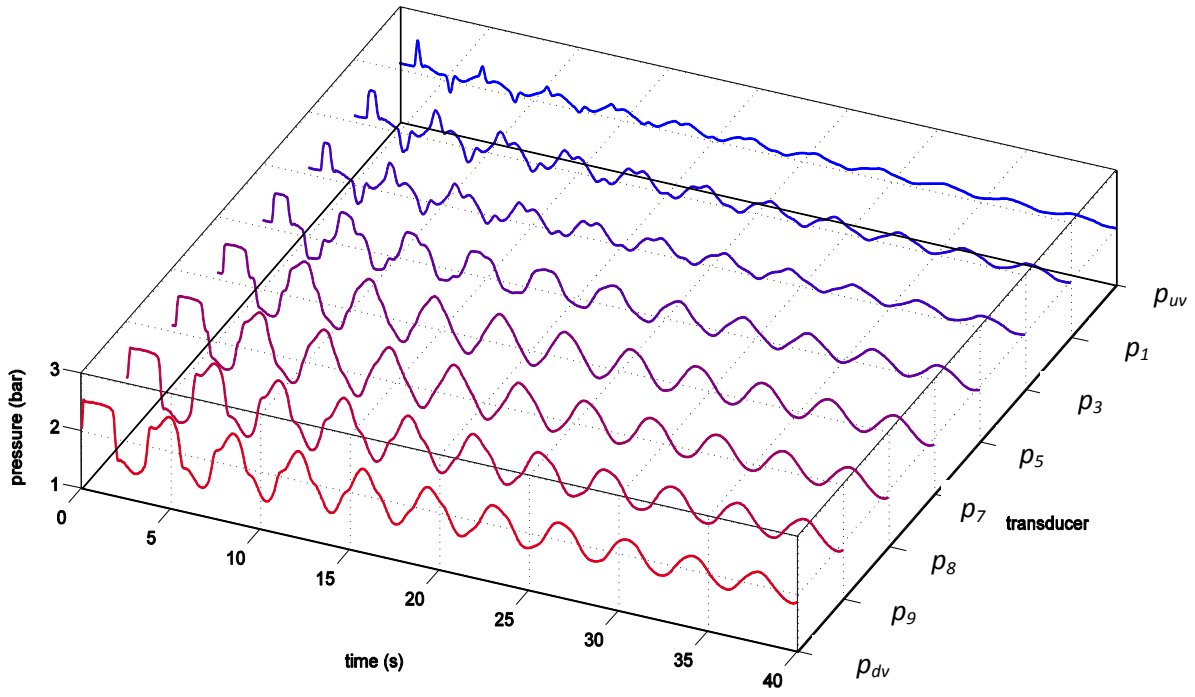


Fig 12. Pressures (averaged over time) measured by the indicated transducers.

5 Conclusions

The following conclusions may be drawn:

1. Detailed measurements of pressures have been presented for a laboratory apparatus including a long PVC pipe with two short steel pipes at its up- and down-stream ends.
2. The results revealed an important advantage with respect to previous similar experimental data from the literature. It was the constant upstream head, which not only simplifies possible future numerical simulations of this experiment, but also guarantees less creep calibration flaws associated with a varying upstream boundary condition.
3. The measured data were interpreted and the dampening effect of the viscoelastic pipe wall on waterhammer pressures was observed. Some important differences with respect to similar experimental results from the literature were pointed out.
4. The results of this experiment reveal that some effects other than the direct influence of rheological behaviour of the pipe wall are involved and they should be taken into account for a precise future comparison with numerical calculations. The influence of the short steel pipes, FSI and unsteady friction are obviously important. Other effects such as nonlinear viscoelastic effects, pipe-wall vibrations, pipe-wall thickness, convective terms and free small gas pockets can partially have important contributions to the transient responses.

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Scientific Professional Quarterly

https://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 23-34

Hydraulic Structures

Shahid Chamran University

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