Experimental characterization of PVC-O pipes for transient modeling
M. Ferrante and C. Capponi

ABSTRACT

The increasing use of plastic materials has modified several aspects of design and management of water distribution systems. With reference to the numerical modeling of transients, the definition of a correct rheological model of the pipe material is receiving an increasing interest. In this paper the behavior of the molecularly oriented polyvinyl chloride (PVC-O) pipes during transients is investigated, by means of tests on a PN16 DN110 pipe installed at the Water Engineering Laboratory of the University of Perugia, Italy. Pipe characteristics, such as wave speed and Kelvin–Voigt parameters, are estimated by the comparison of experimental and numerical results. Analyses are performed both in time and frequency domain. The variation in time of the wave speed is investigated. The results show that, while the wave speed value is close to that of other polymeric material pipes, such as Polyethylene, the viscoelastic behavior is less evident for PVC-O pipes. This feature is of particular interest for research purposes in laboratories and for current use in functioning systems.

Key words | frequency domain, pressurized pipes, PVC-O, transients, viscoelasticity

INTRODUCTION

Because of their pleasing characteristics, in the last decades plastic pipes have been preferred to iron and cast iron pipes for water distribution systems. The reduced costs of acquiring, handling, transportation and installation, combined with the adaptability to earth movement, have consistently spread the putting in place of such pipes in urban environments all over the world.

The two most used plastic materials for pipes are polyethylene (PE), especially the high density polyethylene (HDPE), and polyvinyl chloride (PVC).

Molecularly oriented PVC (known as PVC-O) can be considered such as an improvement of the more conventional unplasticized PVC (PVC-U or PVC). To achieve the molecular orientation, the extruded pipes are firstly enlarged by an increase in the inner pressure at a high temperature and then are cooled, by means of water or air. As a consequence of this process, the tensile strength is almost doubled, giving place to larger internal diameters and reduced weights for the same pipe nominal pressure.

The effects of HDPE and PVC-U pipe material rheology on transients have been largely investigated by numerical and experimental tests (Covas et al. 2005; Duan et al. 2012; Arséno et al. 2013; Pezzinga et al. 2014; Massari et al. 2015; Carrico et al. 2016).

PVC-O rheology has been studied so far mostly by stress and fatigue tests on specimens (Kim & Gilbert 2004; Osry 2005; Robeyns & Vanspeybroeck 2005; West & Truss 2012; Campi et al. 2014). In the framework of the investigations of the pressure-discharge relationship for leaks in pipes of different materials (Greyvenstein & van Zyl 2007; van Zyl & Clayton 2007; Cassa et al. 2010; Ferrante et al. 2011; Ferrante 2012; Massari et al. 2012; Fox et al. 2016; Ssozi et al. 2016).
2016), it has been shown that leak laws for PVC-O pipes have a hysteretical behavior, meaning that the leakage at a given time does not depend only on the pressure but also on its time history and hence different leakage values can correspond to the same pressure value (Ferrante et al. 2015). Some preliminary results of transient tests on PVC-O pipes are presented by Ferrante et al. (2015), where pressure signals, i.e. pressure time histories, are shown during transients. These preliminary transient tests, which led to the design of the tests shown in this paper, were not able to characterize adequately the rheological behavior of the material in the sense that they put forward for consideration a viscoelastic response during transients but did not allow a characterization for practical purposes.

In the following, the experimental set-up and the steady-state hydraulic characterization of the pipe are introduced. With respect to the preliminary tests shown by Ferrante et al. (2015), new experimental transient tests are analyzed in the time and frequency domains and the wave speed dependence on time and frequency is investigated. The viscoelastic properties of the PVC-O pipe are also studied by means of an efficient numerical model based on the impedance method. The reduced computational burden allows the direct scrutiny of the variation of the optimization function in the viscoelastic parameters space. The combined effects of viscoelasticity and unsteady-friction are investigated for the considered test conditions. The optimized numerical model and the implemented viscoelastic component are tested also by means of the measured hoop strains. In the conclusions, remarks on the results are provided and the relevance of the shown tests for the use in laboratory and in water pipeline systems of this material is also explained.

**EXPERIMENTS**

**Experimental set-up**

The tests were carried out at the Water Engineering Laboratory of the University of Perugia, Italy, on the same set-up described in Ferrante et al. (2015) and Ferrante & Capponi (2017) with an oriented polyvinyl chloride (PVC-O) pipe DN110 PN16 – according to ISO 16422 and NFT 54-948 – of length \( L = 105.30 \) m, with an internal diameter \( D = 103.0 \) mm and a wall thickness \( e = 2.7 \) mm (Figure 1). At the downstream end section of the PVC-O pipe, a remotely controlled butterfly valve, MV, was used to generate the transients by means of complete closure maneuvers while a hand operated ball valve, DV, was used to control the initial functioning conditions. An electromagnetic flow-meter, FM, was used to measure the discharge, with an accuracy of 0.2\% of the measured value.

Hoop strains were measured by two strain gages, \( \text{SG}_U \) and \( \text{SG}_D \), where subscripts U and D denote upstream and downstream, respectively. Four piezoresistive pressure transducers (PT), with different full scales (f.s.) and an accuracy of 0.25\% f.s., were used to measure the pressure close to the reservoir (PT_U, 7 bar f.s.), upstream of the maneuver valve (PT_D, 5 bar f.s.) and 0.50 m downstream of the strain gages \( \text{SG}_U \) and \( \text{SG}_D \) (PT_{SGU} and PT_{SGD}, both with a 6 bar f.s.). A pressure transducer in the air vessel \( R \) was also available but since the acquired signals were almost coincident with the signals acquired by PT_U, for the sake of clarity they are not shown in the following. A differential pressure measurement device was also used as explained in the following section. Pressure transducers and strain gages data were acquired at 1 kHz to allow an accurate evaluation of the wave front arrival times. The temperature of the water measured in the reservoir was about 22 °C during the transient test data acquisition.

**Steady-state tests**

To characterize the pipe behavior in steady-state conditions, tests were carried out changing the DV opening degree with MV completely open and waiting until the steady-state
conditions were reached. For 19 different opening degrees, both the discharge and the head losses between the measurement sections of PT_U and PT_D were measured by means of FM and a differential pressure transducer, respectively. The explored discharge ranged from 1.0 to 12.1 L/s, corresponding to velocities between 0.12 and 1.45 m/s and Reynolds numbers from about 1.24 $10^4$ to 1.50 $10^5$. With regard to the practical applications, the explored range of velocities and the set-up pipe diameter are typical for water distribution systems, although lower and higher values of Reynolds number can also be expected. The 19 couples of values of Reynolds number, $Re$, and friction factor, $\lambda$, obtained by the steady-state tests, were in a good agreement with the Blasius smooth pipe law, which was hence used to evaluate the steady-friction in the numerical models. The set-up characteristics did not allow the assessment of the reliability of the Blasius law for higher values of the Reynolds number.

### Unsteady-state tests

Transients were produced in the shown experimental set-up by means of complete closure maneuvers of the MV butterfly valve. The valve control system allowed the variation of two maneuver parameters, i.e. the initial opening degree, $\alpha$, and the angular speed, $\beta$, of MV. The values of these parameters as well as other test characteristics are summarized in Table 1 for the 10 tests carried out. As an example, in Figure 2(a) the pressure signal $H_D$ acquired at PT_D is shown for test 1. To improve the comparison, all pressure signals are relative to the initial steady-state value. The variation of the air vessel R conditions during the transient caused the slow variation in time of the pressure signal at PT_U, $H_U$, shown in the same figure by the solid line. In Figure 2(b) the frequency head response, i.e. the Fourier transform of $H_D$, is plotted against the angular frequency $\omega$.

For the same test 1, in Figure 3(a) the variation in time of all the acquired pressure signals are shown. When a pressure wave reached a measurement section it produced an increase in the pressure signal. Since the pressure wave generated by the MV closure reaches PT_D before PT_SGU and

<table>
<thead>
<tr>
<th>Test</th>
<th>$\alpha$ (°)</th>
<th>$Q_0$ (m³/s)</th>
<th>$\beta$ (°/s)</th>
<th>$t_{\text{max}}$ (s)</th>
<th>$a$ (m/s)</th>
<th>$l_2$ (m)</th>
<th>$E$ (MPa)</th>
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<tr>
<td>1</td>
<td>40</td>
<td>0.0037</td>
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<td>0.13</td>
<td>379.01</td>
<td>188.80</td>
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<td>2</td>
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<td>191.65</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<tr>
<td>5</td>
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</table>

Figure 2 | Variation with time (a) and angular frequency (b) of the pressure head, $H_D$, at the transducer PT_D for test 1. The variation in time of the pressure head at PT_U, $H_U$, is also shown in (a). Hollow circles at the intersections of $H_D$ with $H_U$ denote the pressure wave arrival times.
PTSGD, the pressure signal $H_D$ increased before $H_{SGD}$ and $H_{SGU}$. On the contrary, the R reflected wave reached the measurement sections in the reverse order, and the pressure signal decreased consequently. Although the PTU measurement section was very close to R, the pressure head at PTU was not exactly equal to the pressure head in R and a minor variation of $H_U$ can also be seen in the figure, due to the wave arrival around $t = 0.35$ s.

In Figure 4(a) the pressure signals at PT$_{D}$ are shown for the 10 tests. It can be observed that the two considered values of $\alpha$, and hence of the initial steady-state discharge, $Q_0$, correspond to two different values of the Allievi–Joukovsky overpressure, that is 17.1 m for $\alpha = 40^\circ$ and 27.8 m for $\alpha = 50^\circ$. The variation of $\beta$ implies different maneuver durations, $t_{man}$, and hence wave front steepnesses. The values of $t_{man}$ in Table 1 indicate the duration from the start of the valve opening to its end. It is worth noting that the angular speed does not affect the wave amplitude and hence its variation does not modify the results in terms of the maximum overpressures.

The Fourier transforms of the pressure signals of Figures 3(a) and 4(a) are shown in Figures 3(b) and 4(b), respectively. At low frequencies the peaks denoting the first harmonics of the signals can be pointed out. For the...
tests with low values of $\alpha$ and $\beta$, i.e. with long maneuver duration and low Allievi-Joukovsky overpressure, the noise component is significant and hides the harmonic peaks starting from about $\omega \approx 10$ rad/s.

In Figure 5 the variation in time of the transversal strain measured at $SG_U$ and $SG_D$ is shown. It can be noted that since the pressure head causes the pipe deformation, the correlation between pressure head and strain variation is high.

**ANALYSIS OF THE EXPERIMENTAL DATA**

The wave speed, $a$, is crucial for the determination of the Allievi-Joukovsky overpressure and for the numerical modeling of transients. Wave speed can be determined directly by means of transient tests or indirectly (Wylie et al. 1993; Chaudhry 2013), relating it to the elastic material Young modulus, $E$, by:

$$ a = \sqrt{\frac{k_c}{\rho} \frac{k_D}{1 + k_b \frac{k_c D}{E}}} $$

where $k_c$ and $\rho$ are the water bulk modulus and density, respectively, and the coefficient $k_b$ depends on the pipe constraints (Wylie et al. 1993; Chaudhry 2013).

In the following the PVC-O pipes wave speed is firstly estimated by means of pressure signals acquired during transients. Both time and frequency domains analyses of the signals are performed. Then, by means of the evaluation of $E$ from the measured strains, a calculation of the wave speed based on Equation (1) is also proposed.

**Estimation of the wave speed from the pressure signals**

As mentioned above, the pressure wave arrival at a measurement section produces a sudden gradient in the pressure signal and hence the wave arrival times, $t_W$, can be obtained by means of the interpretation of the pressure signal in the time domain. If the wave speed is constant, the arrival times are linearly related to the travel distance, $L_W$, which can be easily determined considering the position of the measurement section, the length of the pipe and the number of times the wave repeats the same path due to the reservoir and valve reflections.

The arrival times at the measurement section $PT_D$ can be defined by the intersections of the two signals, $H_D$ and $H_U$. In fact, due to the slow variation in time of the pressure in the air vessel, neither the initial nor the final value of $H_U$ can be used as a reference. As an example, in Figure 2(a) the intersections of the two signals for test 1 are marked with hollow circles.

Since the distance between MV and $PT_D$ was about 0.72 m, the approaching and the valve reflected pressure waves were not distinguished and the travel distance of

![Figure 5](https://iwaponline.com/aqua/article-pdf/66/8/606/223335/jws0660606.pdf)
the pressure wave crossing PT_D for the n-th time was evaluated as \( L_W = n2L_t \).

Since the signal to noise ratio decreases with \( \alpha \) and \( \beta \) and it changes in time from test to test, the number of pressure wave arrival times that can be pointed out varies from one test to another. For each test, at least 42 arrival times were determined while the maximum number of 84 arrival times was obtained for test 1.

For a constant wave speed, the relationship between \( L_W \) and \( t_W \) can be expressed as:

\[
L_W = at_W + l_0 \tag{2}
\]

where \( l_0 \) is a fitting parameter.

To estimate the value of \( a \), Equation (2) is fitted to the whole set of data and then separately to the set of data coming from each test. The fitting of Equation (2) to the whole set of data coming from the 10 tests provides the estimate of \( a = 378.4 \) m/s. The results of the fittings of Equation (2) to each test are summarized in Table 1. The estimated values of \( a \) are similar and vary between 378.0 and 379.5 m/s. The effects of this variation on the numerical simulations are discussed in the following. Since the first considered arrival time is given by the first wave reflected from the air vessel, \( l_0 \) values are about \( 2 \) \( L_t \).

The similar pattern of the residuals for each fitting (Figure 6) clearly suggests that they are not normally distributed and are correlated to \( t_W \). Hence Equation (2) does not capture completely the actual functional relationship. The use of the following cubic polynomial expression

\[
L_W = a_3t_W^3 + a_2t_W^2 + at_W + l_0 \tag{3}
\]

improves the fittings in the sense that the pattern of the residuals of Figure 6 disappears. The estimated values of the parameters are \( a_3 = 5.480 \times 10^{-3} \) m/s\(^3\), \( a_2 = 8.695 \times 10^{-2} \) m/s\(^2\), \( a = 375.7 \) m/s, and \( l_0 = 205.9 \) m.

In Figure 7 the results of the fitting of the linear and cubic expressions are compared for test 1. Although the differences in \( L_W \) cannot be appreciated in Figure 7(a), the residual pattern is completely different for the two fittings (Figure 7(c)). The normal probability plot (Figure 7(d)) confirms that the residuals of the cubic fitting (triangles) are closer to the line corresponding to a normal distribution than those of the linear fitting (circles). While Equation (2) assumes that \( a = dL_W/dt_W \) is constant, Equation (3), which improves the fitting, implies a time dependent wave speed, \( a_t \), (Figure 7(b)) defined as:

\[
a_t = 3a_3t_W^2 + 2a_2t_W + a \tag{4}
\]

It is worth noting that the functional dependence of \( a \) on time expressed by Equation (4) is derived by a linear fitting and is not based on physical considerations.

Since \( a_3 \) and \( a_2 \) are several orders of magnitude smaller than \( a \), the difference between \( a \) and \( a_t \) is less than 1.5\%. To assess the effects of such a difference on the pressure signal, the dependence of the wave speed on time defined by Equation (4) was implemented in a classic numerical model based on the method of characteristics (MOC) (Wylie et al. 1995; Chaudhry 2013). Differences between the pressure wave speed determined by the arrival times and the wave speed that determines the characteristic lines are expected (Tijsseling & Vardy 2015) and the inclusion in the MOC of a given time dependence of the wave speed is naive since it disregards the physical reasons of the wave speed variation in time. Nevertheless, as shown, it gives some interesting results.

The implementation in the MOC of the wave speed variation in time implies that, for a given elementary reach length \( \Delta x \), the model requires a variable time step \( \Delta t(t) = \Delta x/a_t(t) \) to be implicitly evaluated at the beginning of each time step. The weak dependence of \( a_t \) on time allows the use of a mean value of \( a_t \) for the considered time step and speeds up the iterative
procedure. In Figure 8 the results of a MOC model using \( a \) and \( a_t \) are compared with the experimental pressure signal \( H_0 = H_D - H_U \) for test 1. While the damping of the signal is not interpreted by the MOC models (Figure 8(a)), the use of \( a_t \) instead of \( a \) assures that the numerical pressure signal is in phase with the experimental one (Figure 8(b)) for the whole simulation.

The angular frequencies corresponding to the peaks of the Fourier transform of the pressure signals, \( \omega_W \), depend on the wave speed. Hence, also the analysis of the pressure signals in the frequency domain can provide an estimation of the wave speed. For the pressure signal at PT_D, located immediately upstream of the valve, the angular frequency of the \( m \)th peak can be evaluated as:

\[
\omega_W = \frac{(2m + 1) \pi a}{2L_t \sqrt{k_D}}
\]

where \( k_D = 1 \) for elastic pipes while it depends on \( \omega \) for viscoelastic pipes (Duan et al. 2012) and \( \omega_p = \pi (2m + 1)/2L_t \). This relationship is explored in Figure 9. The fitting of Equation (5) to the data of the 10 tests provides the value of \( a = 380.7 \text{ m/s} \), with a difference of 0.6% with respect to the value estimated in the time domain. Since a weak dependence of \( a \) on \( t \) has been assessed, the dependence of \( a \) on \( \omega \) is expected but cannot be proven. In fact, due to the increase of the noise component with \( \omega \), only a maximum value of five peaks are considered for the fitting and hence the dependence of \( a \) on \( \omega \) due to \( k_D \) cannot be investigated by means of the fitting residuals (Figure 9).

**Estimation of the wave speed from the measured strains**

Due to the considered pressure head values and pipe geometry, stresses on the transversal direction on the outer surface of the pipe, \( \sigma \), are given by:

\[
\sigma = \frac{\gamma H_D}{2 \pi} \sqrt{\frac{k_p}{a}}
\]

Figure 7 | Comparison of the fittings of Equations (2) and (3) for test 1. The residuals of the fittings in (a) are shown in (c) and in the probability plot for normal distribution (d). The wave speed variations derived by the fittings in (a) are shown in (b).
where $\gamma$ is the water specific weight, and $k_P$ is the parameter that takes into account the variation of the stresses along the radial direction. For the considered geometry, $k_P = 0.9745$ at the outer surface of the pipe.

Measured strains, $\varepsilon$, and stresses calculated by introducing measured pressure heads in Equation (6), are used to investigate the rheological behavior of the PVC-O. In Figure 10, the same test of Figure 5 is analyzed in the $(\varepsilon, \sigma)$ domain. The stresses are expressed in MPa while strains in $\mu\varepsilon$, i.e. $10^{-6}\varepsilon$, and both are relative to the initial values.

Data in Figure 10 do not draw along a straight line as expected for a linear elastic behavior. The narrow spiral,
close to a line, reveals that the rheological behavior of the pipe material depends on time because of a weak viscoelastic effect. The fittings of the data of SGD for each test with a linear relationship, neglecting the probable viscoelastic effect, yield the values for the Young modulus summarized in Table 1. The fitting to all the test data yielded an estimate of the Young modulus of 5,702 MPa. The corresponding value of the wave speed, evaluated by means of Equation (1), is 386.6 m/s with a difference of about 2% with respect to the mean value estimated in the time domain.

THE NUMERICAL MODEL AND THE VISCOELASTIC PARAMETERS

As shown in Figure 8, the variation in time of the wave speed cannot be seen as the reason for the differences between the implemented MOC model and the measured data, but as an effect. This behavior can be explained by two reasons: viscoelasticity and unsteady-friction. In the following both are analyzed.

To characterize the viscoelastic behavior of the PVC-O pipes a Standard Linear Solid model (SL), i.e. a series of one Kelvin–Voigt element and a spring of Young modulus $E_i$, was implemented in an unsteady numerical model of the pipe, without considering the unsteady-friction. A calibration procedure was then used to evaluate the viscoelastic parameters, i.e the Young modulus, $E_r$, and the viscosity, $\eta_r$, of the Kelvin–Voigt spring and dashpot, respectively. To minimize the differences between the simulated and experimental values of $H_D$ for test 1, the Nash–Sutcliffe efficiency, $NS$, was used as the function to be maximized. $NS$ ranges from $-\infty$ to 1, where $NS = 1$ corresponds to a perfect match of modeled and observed data.

Instead of a classical optimization technique (e.g. Covas et al. 2005; Pezzinga 2014), the $NS$ maximization is obtained directly by its evaluation in a whole range of variation of $\eta_r$ and $E_r$. Only these two parameters of the SL model are considered since the value of the third parameter $E_i$ is chosen consistently with the wave speed value of 378.4 m/s estimated in the time domain.

To reduce the computational time, instead of the MOC model, an Impedance Method (IM) model was used (Wylie et al. 1995; Chaudhry 2015). The approximation introduced by the provided frequency domain solution is only related to the linearization of the steady-friction term (Capponi et al. 2017b). In fact, the viscoelastic elements, which can be expressed by convolution integrals, are easily and completely considered by the IM model (Ferrante & Capponi 2007). The reduction of the computational burden allows a large number of simulations and the study of the optimization function in the calibration procedure (Capponi et al. 2017a). For these reasons and for the purposes of this investigation, the introduced approximation can be considered negligible.
In Figure 11, the variation of $NS$ is explored for $E_r \in [10^5; 10^{15}]$ Pa and $\eta_r \in [1; 10^{15}]$ Pa s. In both the $E_r$ and $\eta_r$ considered intervals, $10^2$ logarithmically spaced values are picked, originating a grid of $10^6$ possible parameter combinations. The use of the IM allowed the computation of $NS$ for all the grid nodes in a reasonable time (24.777 $10^3$ s on a 2.7 GHz Intel core i5 computer). It can be noted that the maximum value of $NS = 0.9428$, at the intersection of the dashed lines, is reached for $E_r = 8.31810^{10}$ Pa and $\eta_r = 2.92110^{10}$ Pa s. Such values yield a retardation time $\tau_r = \eta_r/E_r = 0.3511$ s.

The evaluation of $NS$ on such a large range of parameter values allows the shape of the maximization function to be highlighted, which is characterized by a flat region close to the global maximum. The extent of this region is large considering that a logarithmic scale is used for both the axes. To enhance the different sensitivity of the optimization function to the two parameters, two slices of the $NS$ function, denoted by dashed lines in Figure 11, are presented in Figure 12. For the sake of clarity, parameter values are also in logarithmic scale in Figure 12. While for $E_r = 8.31810^{10}$ Pa (Figure 12(b)) the range of $\eta_r$ producing $NS > 0.85$ is relatively narrow and varies in the same order of magnitude, i.e. $10^{10}$, for $\eta_r = 2.92110^{10}$ Pa s (Figure 12(a)) the same values of $NS$ are obtained over several order of magnitude of $E_r$, i.e. between $10^5$ and $10^{11}$.

To assess if the implementation of the viscoelastic model improves the results of the numerical computation, the optimal values of the parameters are used to simulate the experimental variation of pressure head for two tests differing for $\alpha$ and $\beta$ values, i.e. tests 1 and 8 (Figures 13 and 14, respectively). A constant wave speed MOC model is used and the phase shift and the peak damping in the time domain are attributed solely to the viscoelastic effect.

The comparison for test 1 shows that the implementation of the viscoelastic model improves the numerical simulation in the sense that both damping and shift of $H_0$ are well captured (Figure 13). The differences between simulated and experimental signals increase in time and are evident, especially in the phase shift, after about 15 s.

Test 8 has been chosen for a further verification. As shown in Figure 14, the parameters obtained by the calibration on test 1 are able to reproduce, with the same limitations, the transient originated by a maneuver with different $\alpha$ and $\beta$, with $NS = 0.9013$.

Figure 11 | Variation of $NS$ with $E_r$ and $\eta_r$ as a result of $10^6$ simulations. Dashed lines denote the slices in Figure 12 and their intersection corresponds to the maximum $NS$ value.
Figure 12  |  Variation of NS along the two dashed lines in Figure 11.

Figure 13  |  Comparison of the experimental values of $H_0$ for test 1 with the results of a numerical model implementing the calibrated viscoelastic models, with and without the unsteady-friction.
In Figure 15, the simulated stresses and strains at SGD are compared with the experimental ones for test 1. The hysteresis due to the viscoelastic effects of the numerical model interprets the experimental spread around the elastic straight line of the data in the sense that they lay in the same bandwidth.

To evaluate the effects of the unsteady-friction on the shown simulations, the original expression proposed by Bruneone et al. (1995) was implemented in the IM since it was suited for the simulated system. The coefficient that introduces in the model the unsteady-friction was evaluated following Pezzinga (2000) and the parameters of the SL

![Figure 14](image1.png)

**Figure 14** | Comparison of the experimental values of $H_0$ for test 8 with the results of a numerical model implementing the viscoelastic model calibrated on test 1. Unsteady-friction effects are not considered.

![Figure 15](image2.png)

**Figure 15** | Comparison in the stress-strain domain of the experimental and numerical results at SGD for test 1. For the sake of clarity, in (b) a zoom view of the rectangle in (a) is shown.
model were calibrated on the test 1 data. The simulated pressure signal, including both viscoelastic and unsteady-friction effects, is compared in Figure 13 with the experimental signal and the signal obtained calibrating the viscoelastic parameters without considering the unsteady-friction. The obtained value of $NS = 0.9401$ and the comparison of the signals show that the inclusion of the unsteady-friction term in the model does not improve the fitting of the data. This result can be partially explained by the considered test conditions where the viscoelastic effects prevail on the unsteady-friction effects. In fact, the values of the parameter $P$ used by Duan et al. (2010) to evaluate the relative importance of viscoelasticity and unsteady-friction ranges between 53.6 and 77.3 for the shown tests.

**CONCLUSIONS**

In this paper the results of transient tests on a PVC-O pipe are presented, with the aim of characterizing the hydraulic properties of interest for current practice. An experimental steady-state characterization showed a smooth pipe behavior, at least for the considered functioning conditions. The use of a controlled motorized valve allowed ten transient tests to be carried out, differing for the maneuver initial opening degree and the closure velocity.

The frequency domain analysis provides a value of $a = 380.7$ m/s, with a difference of 0.6% with respect to the corresponding time domain value. The noise in the signals prevails after a few harmonics and does not allow the investigation of the frequency dependence of $a$.

The time domain analysis of the tests provides an estimation of the wave speed $a = 578.4$ m/s with a variation in time during the test of about 1.19% around the mean value. Two approaches are then presented to explain this behavior. As a first step, the variation in time of the wave speed is directly implemented in an MOC model. This implementation is naive since it disregards the causes of the wave speed variation in time while it reproduces only one of the effects. This implementation improves the simulation of the signal only for the periodicity, since the simulated signal is in phase with the experimental one for the considered duration. The time dependent wave speed is not able to improve the simulation of the damping.

To investigate the viscoelastic behavior of the pipe as a possible origin of the wave speed variation in time, the strain measures are compared with the measured pressures. The representation of the data in the strain-stress domain reveals a viscoelastic component that is defined as weak because of the dominant elastic behavior.

A characterization of a Standard Linear Solid model (i.e. a series of a spring with a Kelvin–Voigt element) is also proposed as a first step to interpret the data. The parameters are estimated by means of the direct scrutiny of the variation of the Nash–Sutcliffe (NS) coefficient on a wide range of values of the parameters. The use of an IM model allows the examination of $10^6$ simulations in a wide range of variation of the Kelvin–Voigt viscoelastic parameters, i.e $E_r$ and $\eta_r$, within a reasonable time. The introduction of the viscoelastic element in the IM reduces the shift in the wave arrival times and indirectly allows the simulation of the time dependence of the wave speed.

The study of the NS optimization function reveals that the calibration procedure in this case could find many problems in searching the optimal value, which is surrounded by a wide flat region. The sensitivity of $NS$ is different with respect to the Kelvin–Voigt parameters, in the sense that values of $NS$ greater than 0.85 correspond to $E_r$ varying for six orders of magnitude, between $10^5$ and $10^{11}$, while $\eta_r$ for the same $NS$ values is limited by one order of magnitude, i.e. $10^{10}$.

To confirm that the wave speed variation is not an effect of the unsteady-friction, the ‘unsteady-friction’ term was introduced in the numerical model and the calibration procedure was repeated. The obtained results confirmed that in the considered test conditions the viscoelastic effects prevailed on the unsteady-friction effects.

The carried out tests show that the PVC-O wave speed to be used in the numerical models is very close to that of HDPE or similar polymeric material pipes. Besides, the orientation of the molecule chains clearly modifies the rheology of the material, reducing the viscoelastic component with respect to HDPE. The results of this study are interesting for the applications both in laboratories, for research purposes, and in pipeline systems, for normal functioning conditions. In laboratories, PVC-O allows hydraulically long pipe set-ups and fast maneuvers with lengths comparable to those of HDPE and PVC but with a reduced viscoelastic effect. Although in the considered test
the implementation of the unsteady-friction did not significantly improve the match of the model to the observed data, other test conditions could allow investigation of different combinations of unsteady-friction and viscoelastic effects. For practical applications in water pipelines, the given values of the wave speed and viscoelastic parameters, obtained directly on a system and not on specimens, can be used for a proper simulation of the rheology of the material during transients.

Apart from the results about the hydraulic characterization of PVC-O for practical use, the calibration procedure used in this paper recommends the use of NS as optimization function and of the IM model for the analysis of the optimization function in a large range of the parameters.

Further investigations are needed to improve the viscoelastic characterization and test the material in a wide range of geometries and functioning conditions.

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