Comparative assessment of the inline and branching design strategies based on the compound technique

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ABSTRACT

The inline or branching water hammer control strategies, which are based on the insertion of compound plastic short-penstock or inline section at the transient-induced region of main pipes, illustrated a promising ability to upgrade steel pipe-based hydraulic systems concerning the extension of admissible pressure level. In this respect, prior results suggested that the specific layout utilizing an (HDPE–LDPE) compound short-penstock (where the (HDPE) sub-short-penstock is attached to the main steel pipe and the (LDPE) sub-short-penstock corresponds to the short-penstock dead-end side) provided significant attenuation of pressure magnitude. Concurrently, recent studies concluded that the (HDPE–LDPE) compound short-section-based inline strategy provided substantial attenuation of pressure magnitude. However, these strategies illustrated a drawback relying on the expansion of the period of pressure wave oscillations. Accordingly, this study assessed and compared the capacities of the compound technique concerning the trade-off between the magnitude-attenuation and the period-expansion of pressure wave oscillations. The findings of these analyses showed that the (HDPE–LDPE) compound short-penstock particular setup of the branching strategy allowed the best trade-off between the attenuation of magnitude and the period expansion of pressure wave oscillations. Furthermore, results showed the competitiveness of the latter upgrading strategy as compared to the (HDPE) or (LDPE) main pipe-based renewed hydraulic systems.

Key words | branching, compound, HDPE/LDPE, inline, water hammer

HIGHLIGHTS

- The compound technique-based inline or branching design strategies were investigated.
- The HDPE and LDPE plastic materials were investigated.
- The (HDPE–LDPE) compound short-penstock-based protected system provided the best trade-off between magnitude and period of pressure wave oscillations.
INTRODUCTION

Water supply systems operate over a broad range of operating regimes. Occasionally, the improper setting of hydraulic parts or the breakdown of hydraulic machinery leads to large magnitudes of pressure wave fluctuations and may even cause the onset of a cavitating flow regime. Depending on the magnitude of these pressure surges, commonly referred to as water hammer surge-waves, the hydraulic system may experience undesirable effects (e.g. perturbation in serviceability, structural vibrations, and excessive noise) or extensive costly damages (e.g. pipe collapse or bursting, rupture of the piping system); and the operators’ safety may even be risked (Bergant & Simpson 1999; Thorley 2004; Besharat et al. 2015; Zhang et al. 2018; Du et al. 2020). It is, hence, essential to anticipate and mitigate excessive water hammer surges in the design stage of water supply systems and to define safe operation guidelines of these systems in advance. Generally, the prediction of ultimate transient pressure wave magnitudes is used to verify whether the selected pipe material, thicknesses, and pressure class are appropriate to withstand predicted pressure loads to avoid pipe rupture or system damage. Besides, the period value of pressure wave oscillation is used to set out the operational procedures of hydraulic parts.

From a design standpoint, water hammer surges should be kept within a prescribed limit using a combination of different classical design measures ranging from the adjustment of operational procedures and the installation of surge control devices to the redesign of the original pipeline layout. It is interesting to highlight herein that the cumulative use of different control devices may adversely affect the water hammer courses, due to inconsistency between the nature of included devices (Boulos et al. 2005; Jung et al. 2007, 2008, 2009; Seog-Jung & Karney 2009; Chen et al. 2015). Besides, the prediction of flow parameters is complicated furthermore by the non-linear behavior of embedded surge control devices. In this regard, Jung et al. (2007, 2008, 2009) concluded that even modern computer systems cannot cope with the computational challenges brought by a strict and systematic search for the best system protection in most practical field applications.

Alternatively to the classic design measures cited above, and benefitting from the mechanical behavior of plastic materials, certain concepts of water hammer control strategies have been addressed in the literature. Incidentally, these studies aimed at upgrading the capacities of existing pressurized steel-piping systems in terms of admissible pressure level. Principally, these strategies included the inline concept (Figure 1(a)), which is based on the substitution of a short section of the main steel-piping system by another one made of plastic material; and the branching concept (Figure 1(b)), which is based on adding a plastic...
short-penstock at the transient-induced region of the main pipe (Massouh & Comolet 1984; Pezzinga & Scandura 1995; Triki 2016, 2017, 2018a, 2018b; Gong et al. 2018; Fersi & Triki 2019; Triki & Chaker 2019, 2020; Chaker & Triki 2020a, 2020b; Kubrak & Kodura 2020). Results have shown that these two concepts allow promising improvement of the admissible pressure of existing hydraulic installations without making significant modifications. Nevertheless, previous investigations unveiled that the use of plastic material induces an expansion effect (i.e. an increase) of the period of pressure wave oscillations. Incidentally, the expansion effect of the period of pressure wave oscillations may negatively affect the operational procedures of hydraulic services, such as the increase in critical time for closing the valve. Consequently, the use of plastic material types leads to a conflict between two design factors including the attenuation of magnitude and the expansion of the period of pressure wave oscillation. Physically, the attenuation of pressure head magnitude is mainly attributed to the reduced modulus of the used material for the short-section, and the expansion effect of the period of pressure wave oscillations is due to the retarded response of viscoelastic materials (Ramos et al. 2004; Brinson & Brinson 2008; Duan et al. 2010a; Mitosek & Szymkiewicz 2012; Evangelista et al. 2015; Ferrante & Capponi 2017; Pan et al. 2020, 2021). Precisely, previous researches showed that the LDPE plastic material type allows more attenuation of the pressure surge magnitude than the HDPE one; and inversely, the latter concept offers less expansion of the period of pressure wave oscillations than the first one.

Subsequently, in order to address the foregoing drawback of the conventional technique of implementation of the inline and branching concepts, Triki & Chaker (2019) and Chaker & Triki (2020a) proposed the compound technique, which is based on splitting the single short-section or short-penstock, used in the conventional technique-based inline or branching strategy, into two sub-short-sections made up of two distinct plastic material types. This technique was intended to combine the merits from the large pressure attenuation allowed by the LDPE material type and the low expansion of pressure wave oscillation period capacities provided by the HDPE material type. Triki & Chaker (2019) demonstrated that the upgraded system layout based on an (HDPE–LDPE) compound inline-short-section (where the HDPE sub-short-section is attached to the hydraulic parts, while the LDPE one is attached to the main steel pipe) leads to the best trade-off between the magnitude-attenuation and period-expansion factors, within the compound technique-based branching strategy framework. Concurrently, Chaker & Triki (2020a) concluded that the particular setup of the compound technique-based branching strategy employing an (HDPE–LDPE) compound short-penstock allows the best trade-off
(i.e. magnitude-attenuation and period-expansion), within the compound technique-based branching strategy framework. Accordingly, this research aims at gaining further insight into the water hammer control topic by comprehensively assessing and comparing the capacities of the compound technique-based inline and branching strategies in terms of the trade-off (between the magnitude-attenuation and period-expansion effects of transient pressure wave oscillations) provided by an (HDPE–LDPE) compound inline-short-section and that allowed by an (HDPE–LDPE) compound short-penstock. Additionally, this investigation looks into the benefits of the former upgrading strategies in comparison with the total renewal of the main-piping systems using HDPE or LDPE plastic materials.

In the next section, the methodology used for approximating the flow parameters is briefly outlined.

**METHODOLOGY**

From a computational point of view, different approaches can be used for hydraulic transient analysis, including simplified approaches used for extreme pressure surge magnitude estimation (such as the Joukowski law for rapid maneuvers, and the Michaud formula for slow maneuvers), classical transient solvers which are based on a set of simplifications, and complete transient solvers which account for different dynamic effects (e.g. unsteady friction loss, non-elastic pipe-wall behavior, fluid-structure interaction, or cavitation). In this line, the 1-D Extended Water Hammer Model (1-D-EWHM) embedding the Kelvin–Voigt (Aklonis et al. 1972) and Vitkovsky et al. (2000) formulations, is typically implemented to analyze fast transient events in plastic pipes (Covas et al. 2004; Ghidaoui et al. 2005; Wood et al. 2005; Duan et al. 2010b; Duan et al. 2012; 2018; 2020; Carrico et al. 2016; Bertaglia et al. 2018; Walters & Leishear 2018; Cao et al. 2020; Lashkarbolok & Tijsseling 2020; Warda et al. 2020). Accordingly, this formulation is selected in the present study.

Briefly, the 1-D-EWHM equating fast transient behavior in elastic and plastic pressurized pipes may be written as follows (detailed derivations are reported in Covas et al. 2004) and Triki (2017, 2018a, 2018b):

\[
\frac{\partial H}{\partial t} + \frac{a_0^2}{gA} \frac{\partial Q}{\partial x} + 2 \frac{a_0^2}{g} \frac{\partial \varepsilon_t}{\partial t} = 0 \quad \text{and} \quad 1 \frac{\partial Q}{A \partial t} + \frac{\partial H}{g \partial x} + g(h_{h_c} + h_{e_c}) = 0
\]

where \( H \) = pressure head; \( Q \) = discharge; \( A \) = pipe cross-section area; \( g \) = gravity acceleration; \( a_0 = \sqrt{K/\rho}/1 + \xi(D/e)K/6 = \text{elastic-wave-speed}; \) \( K \) = bulk elasticity modulus of the fluid \((K = 2.19 \text{ GPa, for water}); \) \( \rho \) = mass density of the fluid \((\rho = 999 \text{ kg/m}^3, \text{for water}); \) \( \xi \) = dimensionless parameter describing pipe constraint condition \((\xi = 1.04, \text{for thin-wall elastic pipes (Wylie & Streeter 1993)})); \( J_0 \) = elastic creep compliance of the pipe-wall material; \( h_{h_c} \) = quasi-steady pressure head-loss component per unit length, computed from the Colebrook–White \((h_{h_c} = f(Q)/Q/(2DA)^2) \) and the Hagen–Poiseuille \((h_{h_c} = 32\nu Q/(gD^2A)) \) formulas, for turbulent and laminar flow, respectively; \( f \) = Darcy–Weisbach friction factor; \( \nu \) = fluid kinematic viscosity; \( D \) = inner diameter; \( e \) = pipe-wall thickness; \( x \) = distance along the pipe centerline; and \( t \) = time.

The unsteady friction component \( h_{e_c} \) is expressed referring to the Vitkovsky et al. (2000) formulation:

\[
h_{e_c} = \frac{k_v}{gA} \left( \frac{\partial Q}{\partial t} + a_0 \text{Sgn}(Q) \frac{\partial |Q|}{\partial x} \right)
\]

where \( k_v = 0.03 \) = Vitkovsky et al. (2000) decay coefficient; and ‘Sgn’ = sign of the discharge.

The retarded radial strain may be written according to Aklonis et al. (1972):

\[
\varepsilon_r = \int_0^t \frac{\alpha'(t-s)D(t-s)}{2e(t-s)} \left[ p(t-s) - p_0 \right] \frac{\partial J(s)}{\partial s} \, ds
\]

where \( p \) = pressure; \( J \) = creep-compliance function.

In the above equation, the creep-compliance function \( J(t) \) may be evaluated using the generalized Kelvin–Voigt linear-viscoelastic model (Figure 2) as follows (Aklonis
backward compatibility equations (Wylie & Streeter 1993; Triki et al. 2017): 

\[ f(t) = f_0 + \sum_{k=1}^{n_{kw}} f_k (1 - e^{-t/t_k}) \]  

where \( f_k = 1/E_k = \text{creep compliance and } \tau_k = \mu_k/E_k \) (\( k = 0 \cdots n_{kw} \)) = retardation time of the dashpot of the \( k \)th Kelvin–Voigt element, respectively, \( n_{kw} \) = number of Kelvin–Voigt elements, \( E_k = \text{Young modulus of the spring and } \mu_k \) (\( k = 1 \cdots n_{kw} \)) = viscosity of the \( k \)th Kelvin–Voigt element, respectively.

The 1-D-EWHM (Equation (1)) may be solved using a Method of Characteristics-based algorithm, established upon a specified time-step rectangular grid (STS-MOC). It is worth noting that this algorithm was validated earlier by the author against experimental data presented by Covas et al. (2004) (e.g. Triki 2017; Triki & Chaker 2019; Chaker & Triki 2020a, 2020b)).

Briefly, the finite difference-based numerical discretization of the 1-D-EWHM leads to the following forward and backward compatibility equations (Wylie & Streeter 1993; Triki 2017, 2018a, 2018b; Triki & Chaker 2019; Chaker & Triki 2020a, 2020b):

\[
\frac{C_{v}}{A} \frac{\partial H}{\partial t} + \frac{a_{0}}{g} \frac{\partial Q}{\partial t} + 2a_{0} \left( \frac{\partial \psi}{\partial t} \right) \pm a_{0} \frac{\partial H}{\partial t} = 0 \quad \text{along} \\
\Delta v = \pm \frac{a_{0}}{C_{r}} \Delta t
\]

where \( j = \text{pipe number (} 1 \leq j \leq np \); \( i = \text{section index (} 1 \leq i \leq n_{s} \)); \( n_{s} \) = number of sections of the \( j \)th pipe, \( n_{p} \) = number of pipes, and \( \Delta t \) = time-step increment chosen referring to the CFL rule.

Besides, the STS-MOC-based solver is combined with the discrete gas cavity model (DGCM) to describe the cavitating flow behavior (Wylie & Streeter 1993; Pezzinga & Cinzia Santoro 2020; Warda et al. 2020). For instance, the cavity volume obtained from the discretization of the continuity equation, associated with the cavity zone, is:

\[
\psi_{i}^{t} = (Q_{i}^{t-2\Delta t} + [\psi(Q_{i}^{t} - Q_{ai}^{t}) - (1 - \psi)(Q_{i}^{t-2\Delta t} - Q_{ai}^{t-2\Delta t})]) \\
\times 2 \times \Delta t
\]

where \( Q \) and \( Q_{ai} \) = average discharges at the up- and down-stream side of the cavity zone during the \( \Delta t \) period, respectively; and \( \psi \) = weighting factor (0.5 \( \leq \psi \leq 1 \)).

In addition, the discretized form of the perfect gas law for the isothermic evolution of the cavity reads:

\[
\psi_{i}^{t} \times (H_{i}^{t} - z_{i} - H_{0}) = (H_{0} - z_{i} - H_{0}) \times \alpha_{0} \times A \times \Delta t
\]

in which \( H_{0} \) = reference pressure head; \( \alpha_{0} \) = void-fraction at \( H_{0} \); \( z_{i} \) = pipe elevation; and \( H_{0} \) = gauge vapor pressure head of the liquid (\( H_{0} = -10.2 \text{ m for water} \)).

It is worth noting that the cavity collapses inasmuch as \( \psi < 0 \).

Incidentally, the hydraulic parameters at an inline or branched connection are evaluated under the assumptions of no flow storage and common pressure grade-line elevation (Wylie & Streeter 1993; Wan & Huang 2018). Accordingly, the discharge and pressure head parameters at the connection of the plastic short-penstock with the main steel pipe are linked as follows:

\[ Q_{x=L}^{j-1} = Q_{x=0}^{j-0} + Q_{\text{short-penstock}}^{j-0} \]

and \( H_{x=L}^{j-1} = H_{x=0}^{j} = H_{\text{short-penstock}}^{j} \)

Similarly, the flow parameters at the inline connection of (sub-)short-penstocks or -sections, are evaluated as:

\[ Q_{x=L}^{j-1} = Q_{x=0}^{j-0} \quad \text{and} \quad H_{x=L}^{j-1} = H_{x=0}^{j} \]
Ultimately, the stability condition of the STS-MOC-based solver outlined above is ensured based on the Courant–Friedrichs–Lewy criterion:

$$\Delta x = \frac{\Delta t}{c_{j}}$$

where $c_{j}$ is the Courant number associated with the jth pipe, chosen in the range $c_{j} \leq 1$ (Wylie & Streeter 1993; Wan & Huang 2018).

**Validation of the numerical model**

Data from laboratory experiments conducted by Covas et al. (2004) are used to validate the numerical model developed above. The experimental apparatus investigated by the authors pertains to a reservoir-HDPE pipe-valve system. The pipe characteristics are $q_0 = 1.008$ L/s and $h_{0}^{\text{fl}} = 35$ m, respectively. Results are carried out for a transient flow initiated by the abrupt closure of the downstream valve. One notes that the next numerical computations are performed by the STS-MOC procedure developed earlier, using a specified time step $\Delta t = 0.016$ s and a Courant number $c_{r} = 1$.

Figure 1 compares the measured pressure head signals and computed one involved by the water hammer solver embedding the Vitkovsky and Kelvin–Voigt formulations. This figure shows that the pressure head signal predicted by the 1-D-EWH equations based on the Vitkovsky and Kelvin–Voigt formulations complies well with the measured data, in terms of magnitude and the phase shift of the first cycle of wave oscillation.

Table 1 | Values of pressure head magnitudes versus time-steps

| Time-steps (s) | 0.016 | 0.008 | 0.004 | 0.002 |
|----------------|-------|-------|-------|-------|
| $H_{\text{up-surge}}$ (m) | 19.5 | 19.5 | 19.4 | 19.5 |

Incidentally, it is worth pointing out that the pressure wave magnitudes calculated based on the Joukowsky law are greater than the observed and computed magnitudes using the 1-D-EWH equations. In this respect, the Joukowsky pressure magnitudes corresponding to the HDPE main-piping system is $\Delta H_{\text{Joukowsky}} = 21.9$ m, while the observed magnitude is equal to $\Delta H_{\text{observed}} = 18.45$ m and the predicted one using the 1-D-EWH equations is equal to $\Delta H_{1\text{-D-EWH}} = 19.5$ m. Likewise, the theoretical period values computed for the HDPE or LDPE main-piping systems (i.e. $T_{1}^{\text{HDPE}} = 1.33$ s) are significantly lower than those collected from the pressure wave curves issued from the observed signal and the predicted one using the 1-D-EWH equations (i.e. $T_{1}^{\text{observed}} = 3.21$ s and $T_{1}^{1\text{-D-EWH}} = 3.19$ s, respectively). Physically, these dispersions are substantially due to the retarded response involved by the viscoelastic behavior of plastic material.

From the numerical side, exploration of the sensitivity of the values of pressure head magnitudes to the time-step size, listed in Table 1, suggests that the decrease in the time step does not significantly affect the value of the first pressure peak.

**CASE STUDY**

In the following, the performances of the compound technique are assessed within the inline and branching strategy concepts. The HDPE or LDPE plastic material types are employed for the (sub-)short-sections or -penstocks. The mechanical characteristics of employed pipe-wall materials are listed in Table 2 (Keramat & Haghighi 2014).

For comparison purposes, previous results associated with the upgraded system cases, based on the conventional technique-based layout of the inline or branching concepts, are also addressed (Triki 2016, 2017, 2018a; Triki & Fersi 2018; Fersi & Triki 2019). In this regard, in order to ensure a consistent comparison in terms of plastic material volume employed in each upgraded system layout, the length and diameter values of the (sub) short-sections utilized in the conventional and compound techniques are
linked as follows:

\[
\delta H_{\text{compound}} = \frac{\delta H_{\text{conventional}}}{2} \quad \text{and} \quad \beta_{\text{compound}} = \beta_{\text{conventional}}
\]

One notes that the next numerical computations were carried out using the set of input parameters for the STS-MOC-based procedure: \(\Delta t = 0.017 \text{ s}; c_{\text{steel}} = 0.9841\); and \(c_{\text{plastic short-section}} = 1\).

The next results interpreting the up- or down-surge pressure wave characteristics are denoted by the symbols (+) or (−), respectively; and, the symbol prime (′) is assigned to the branching concept. Furthermore, the following definitions are used in the next result interpretations: (i) the magnitude of up- or down-surge pressure wave is evaluated as: \(\Delta H_{\text{up/s}} = |H_{\text{max/min}} - H_0|\); (ii) the attenuation of the up- or down-surge pressure wave involved the controlled system cases as compared to those associated with original system case are computed as: \(\delta H_{\text{HDPE/LDPE}} = |H_{\text{steel}} - H_{\text{HDPE/LDPE}}|\); and (iii) the phase shift between the first cycle of pressure wave oscillations involved in the controlled system cases and their counterparts associated with the original system case is computed as \(\varphi_{\text{HDPE/LDPE}} = |T_{\text{steel}} - T_{\text{HDPE/LDPE}}|\).

Case 1

The original hydraulic system considered in this subsection is sketched in Figure 3(a). The steel pipe specifications are \(L = 100 \text{ m and } D = 53.2 \text{ mm}\). Initially, a steady-state flow regime was established for constant values of the discharge and the pressure head at the upstream tank: \(Q_0 = 0.58 \text{ L/s and } H_0^{\text{Reservoir}} = 45\text{m} \), respectively; before a transient event caused by the abrupt and full closure of the downstream valve. Such an event may be described as follows:

\[
Q_{x=L} = 0 \quad \text{and} \quad H_{x=0} = H_0^{\text{Reservoir}}(t > 0) \quad (12)
\]

In such a situation, the compound technique-based inline strategy consists of substituting a downstream short-section of the original steel-piping system by an (HDPE–LDPE) compound short-inline section, where the (HDPE) and (LDPE) sub-short-sections are attached to the main steel pipe and valve, respectively (Figure 3(b)). However, the compound technique-based branching strategy consists of installing an (HDPE–LDPE) compound short-penstock at the downstream extremity of the piping system, where the (HDPE) sub-short-penstock is attached to the main steel pipe and the (LDPE) sub-short-penstock corresponds to the dead-end side of the short-penstock (Figure 3(c)).

The diameter and length values of the sub-short-sections or penstocks are selected equal to: \(\delta_{\text{compound}} = 2.5 \text{ m and } \delta_{\text{conventional}} = 53.2 \text{ mm}\). Thereupon, referring to Equation (12), the results associated with the conventional technique-based inline or branching concepts are addressed for the short-section or penstock diameters and lengths equal to: \(\delta_{\text{short-section}} = 5 \text{ m and } \delta_{\text{short-section}} = 53.2 \text{ mm}\).

Figure 3 illustrates the estimates of downstream pressure wave signals predicted into the original system case and their counterparts involved by the upgraded system cases based on an (HDPE–LDPE) compound short-inline section or short-penstock, and (HDPE) and (LDPE) conventional short-sections or -penstocks. Besides, the renewed hydraulic system cases corresponding to main pipe systems made of HDPE, or LDPE plastic pipe, are also reported in this figure to check the usefulness of the inline upgrading strategy for the

Table 2 | Characteristics of employed materials

| Pipe-wall materials | Wave-speed \(a_0\) (m/s) | \(J_0\) (GPa\(^{-1}\)) | \(J_1\) (GPa\(^{-1}\)) | \(\tau_1\) (s) | \(J_2\) (GPa\(^{-1}\)) | \(\tau_2\) (s) | \(J_3\) (GPa\(^{-1}\)) | \(\tau_3\) (s) | \(J_4\) (GPa\(^{-1}\)) | \(\tau_4\) (s) | \(J_5\) (GPa\(^{-1}\)) | \(\tau_5\) (s) |
|---------------------|------------------------|----------------------|----------------------|--------------|----------------------|--------------|----------------------|--------------|----------------------|--------------|----------------------|--------------|
| Steel               | 1,369.9                | 0.0049               | -                    | -            | -                    | -            | -                    | -            | -                    | -            | -                    | -            |
| HDPE                | 404.9                  | 0.6990               | 1.057                | 0.05         | 1.054                | 0.5          | 0.905                | 1.5          | 0.262                | 5.0          | 0.746                | 10.0         |
| LDPE                | 263.9                  | 1.5400               | 7.54                 | 0.000089     | 10.46                | 0.022        | 12.37                | 1.864        | -                    | -            | -                    | -            |
complete renovation of the hydraulic system. Jointly, the data in Table 3 specify completely the features of the first cycle of the wave curves plotted in Figure 4.

At first glance, the pressure wave patterns corresponding to the upgraded and renewed system cases illustrate amortized trends of first peaks and crests accompanied by

**Table 3 | Characteristics of the pressure waves in Figure 4**

| Parameters       | Steel main pipe | Plastic main pipe | Conventional technique | Compound technique |
|------------------|-----------------|-------------------|------------------------|-------------------|
|                  |                 | HDPE   | LDPE   | Inline    | Branching    | Inline    | Branching    | Inline-HDPE-LDPE | Branching-LDPE-HDPE |
| $T_1$ (s)        | 0.420           | 1.264  | 1.566  | 0.620     | 0.710       | 0.610     | 0.700       | 1.026               | 0.984               |
| $H_{\text{max}}$ (m) | 85.6           | 56.4   | 49.2   | 77.9      | 65.3        | 80.2      | 67.7        | 71.9                | 68.8                |
| $H_{\text{min}}$ (m) | 5.4            | 37.0   | 41.5   | 17.7      | 27.5        | 17.7      | 27.5        | 21.9                | 24.0                |
| $H_{\text{up-surge}}$ (m) | 40.6         | 11.4   | 4.2    | 32.9      | 20.3        | 35.2      | 22.7        | 26.9                | 23.8                |
| $H_{\text{down-surge}}$ (m) | 39.6         | 8.0    | 3.5    | 27.3      | 17.5        | 27.3      | 17.5        | 23.1                | 21.0                |
expansions of the period values pressure wave oscillations, as compared with the original system case. Thereby, to classify the different system layouts, the magnitudes of up- and down-pressure surges versus the period for the first cycle of pressure wave oscillations are reported in Figure 5.

Inspection of Figures 4 and 5 and Table 3 reveals that the larger up- and down-pressure surge magnitudes are associated with the original system case: $\Delta H_{\text{steel}} = 40.6$ m and $\Delta H_{\text{steel}} = 40.6$ m, respectively; however, less important magnitudes are involved by the upgraded system cases utilizing an (HDPE–LDPE) compound short-inline section or short-penstock. In this regard, the attenuations of up- and down-pressure surge magnitudes involved by the upgraded system cases utilizing an (HDPE–LDPE) compound short-inline section or short-penstock are $\delta H_{\text{HDPE–LDPE}} = 5.4$ m and $\delta H_{\text{HDPE–LDPE}} = 19.5$ m or $\delta H_{\text{HDPE–LDPE}} = 16.8$ m and $\delta H_{\text{HDPE–LDPE}} = 18.6$ m, respectively.

On the other hand, Figures 4 and 5 and Table 3 reveal that the periods of the first cycle of pressure wave oscillations estimated in the upgraded system cases built upon an (HDPE–LDPE) compound short-inline section or short-penstock are $T_{\text{HDPE–LDPE}} = 1.026$ s or $T_{\text{HDPE–LDPE}} = 0.894$ s, respectively; while the corresponding period, involved by the original system case, is equal to: $T_{\text{steel}} = 0.42$ s. This implies that the plastic material types of the compound short-inline section or short-penstock induce the expansion of the pressure wave oscillation period. Specifically, the phase shifts between an (HDPE–LDPE) compound short-inline section or short-penstock-based layouts of the upgraded system and their counterpart predicted into the original system case are $\phi_{\text{HDPE–LDPE}} = 0.606$ s or $\phi_{\text{HDPE–LDPE}} = 0.564$ s, respectively.

These results imply the ratios between the attenuations of up- and down-surge magnitudes and the phase shift involved by the (HDPE–LDPE) compound short-inline
section or short-penstock-based setups of upgraded systems: \( \alpha_{\text{HDPE-LDPE}} = 9.0 \text{ m/s} \) or \( \alpha_{\text{HDPE-LDPE}} = 20.2 \text{ m/s} \) and \( \alpha_{\text{HDPE-LDPE}} = 29.7 \text{ m/s} \) or \( \alpha_{\text{HDPE-LDPE}} = 33.0 \text{ m/s} \), respectively.

On this point, it may be concluded that the compound technique-based branching concept utilizing an (HDPE–LDPE) compound short-penstock leads to a better trade-off between the attenuation of the magnitude and the expansion of the period of pressure wave oscillations than the compound technique-based inline concept.

Incidentally, the former compound technique setup provides more important amortization of magnitudes of up- and down-pressure surges and more important expansion of the period of pressure wave oscillations, than the (HDPE) or (LDPE) short-penstock-based setups of conventional technique. Indeed, the attenuations of up- and down-pressure surge magnitudes involved by upgraded system cases build upon (HDPE) or (LDPE) short-penstocks are \( \delta H_{\text{HDPE}} = 20.3 \text{ m} \) and \( \delta H_{\text{LDPE}} = 22.1 \text{ m} \) or \( \delta H_{\text{LDPE}} = 17.9 \text{ m} \) and \( \delta H_{\text{LDPE}} = 22.1 \text{ m} \), respectively. Additionally, the phase shifts calculated between an (HDPE) or (LDPE) short-penstock-based layout of upgraded systems, and their counterpart predicted into the original system case are \( \phi_{\text{HDPE}} = 0.200 \text{ s} \) or \( \phi_{\text{LDPE}} = 0.290 \text{ s} \), respectively. In return, the ratios between the attenuations of up- and down-surge magnitudes and the phase shift involved by the (HDPE) or (LDPE) short-penstocks-based upgraded systems are \( \alpha_{\text{HDPE}} = 72.2 \text{ m/s} \) or \( \alpha_{\text{HDPE}} = 86.9 \text{ m/s} \) and \( \alpha_{\text{LDPE}} = 27.4 \text{ m/s} \) or \( \alpha_{\text{LDPE}} = 43.7 \text{ m/s} \), respectively.

Incidentally, the renewed system cases utilizing HDPE or LDPE main pipe-based renewed system cases lead to a more substantial reduction of pressure wave magnitude than that involved by the original system case. In this respect, the attenuations of up- and down-pressure surge magnitudes involved by an HDPE or LDPE main pipe are \( \delta H_{\text{HDPE-mainpipe}} = 13.7 \text{ m} \) and \( \delta H_{\text{LDPE-mainpipe}} = 16.5 \text{ m} \) or \( \delta H_{\text{LDPE-mainpipe}} = 7.8 \text{ m} \) and \( \delta H_{\text{LDPE-mainpipe}} = 12.2 \text{ m} \), respectively. However, the foregoing renewed system layouts induce significant expansion of the period of the first cycle of pressure wave oscillations, as compared to upgraded system setup based on an (HDPE–LDPE) compound short-penstock. Specifically, the phase shifts between an (HDPE) or (LDPE) main pipe-based layout of the renewed systems, and their counterparts predicted into the original system case are \( \phi_{\text{HDPE-mainpipe}} = 0.190 \text{ s} \) or \( \phi_{\text{LDPE-mainpipe}} = 0.564 \text{ s} \), respectively.

In summary, the above results attest that the (HDPE–LDPE) compound short-penstock-based setup of the upgraded system allows more attenuation of the first pressure head peak and crest as compared to the original system case and the upgraded systems cases involving an (HDPE) or (LDPE) setup of the conventional technique-based branching or inline concepts. Conversely, the former compound technique setup leads to more important expansion of the period of pressure wave oscillations than the original system case and the conventional technique setups-based branching or inline concepts.

**Case 2**

The original hydraulic system, considered in this subsection, consists of a sloping steel-piping system connecting two pressurized tanks and equipped with a valve at its inlet (Figure 6(a)). The characteristics of the steel-piping system are \( L = 100 \text{ m} \) and \( D = 53.2 \text{ mm} \). The upstream tank
level is $z_u = 2.03\, \text{m}$ above the downstream pipe axis. The initial flow velocity in the piping system is: $v_0 = 1.04\, \text{m/s}$, corresponding to a constant pressure head $H_0^x = 21.4\, \text{m}$ in the downstream tank. The water hammer event corresponds to the abrupt and full closure of the upstream valve. The boundary conditions corresponding to such an event may be expressed as follows:

$$Q_{x=0} = 0 \quad \text{and} \quad H_{x=L} = H_0^x (t > 0) \quad (13)$$

In this case, the implementations of the compound technique-based inline and branching concepts are schematized in Figure 6(b) and 6(c), respectively. It is interesting to delineate that the (HDPE) sub-short-inline section or short-penstock are attached to the main steel pipe; however, the (LDPE) sub-short-inline section is attached to the main steel pipe and the (LDPE) sub-short-penstock corresponds to the dead-end side of the short-penstock.

The investigation addresses the length and diameter values of the sub-short-inline sections or short-penstocks equals to: $l_{\text{compound \ sub-short-section}} = 5\, \text{m}$ and $d_{\text{compound \ sub-short-section}} = 53.2\, \text{mm}$. Hence, as per Equation (12), the length and diameter values of the short-inline section or short-penstock used in the conventional technique framework are equal to: $l_{\text{conventional \ short-section}} = 10\, \text{m}$ and $d_{\text{conventional \ short-section}} = 53.2\, \text{mm}$.
Figure 7 shows the upstream pressure wave signals, computed into the original system case along with their counterparts estimated into the upgraded system cases based on an (HDPE–LDPE) compound short-inline section or short-penstock, and (HDPE) and (LDPE) short-sections or short-penstocks. Additionally, the renewed hydraulic system cases corresponding to main pipe systems made of HDPE, or LDPE plastic pipe, are also reported in this figure to check the usefulness of the inline upgrading strategy for the complete renovation of the hydraulic system. Jointly, the main features of the first cycle of the wave patterns plotted in Figure 7 are enumerated in Table 4.

At first sight, Figure 7 shows that the cavitating flow regime is established in the original system case. For instance, the pressure head signal first drops to the saturated pressure head value of the liquid (i.e. $H_{\text{min}} = 10.2$ m); and, subsequently, rises to $H_{\text{max}} = 63.7$ m, due to the superposition of the surge wave involved by the valve closure and the wave generated by the collapse of the vapor cavity. In this regard, the up- and down-pressure surge magnitudes are $\Delta H_{\text{steel}} = 41.7$ m and $\Delta H_{\text{steel}} = 32.2$ m, respectively.

Alternatively, Figure 7 suggests that the cavitation is removed from all upgraded system cases. Furthermore, the pressure wave signals illustrated attenuated and expanded profiles. As for the first case study, to classify the different upgraded system layouts, the magnitude-period nexus is shown in Figure 8, for the first cycle of pressure wave oscillations.

Concerning the compound technique-based inline or branching concepts, the amortization of up- and down-pressure surge magnitudes involved by an (HDPE–LDPE) compound short-inline section or short-penstock are {$\delta H_{\text{HDPE–LDPE}} = 19.2$ m and $\delta H_{\text{HDPE–LDPE}} = 9.4$ m} or {$\delta' H_{\text{HDPE–LDPE}} = 25.5$ m and $\delta' H_{\text{HDPE–LDPE}} = 13.8$ m}, respectively.

On the other hand, Figures 7 and 8 and Table 4 suggest that the upgraded system-based branching strategy setup using an (HDPE–LDPE) compound short-penstock induces less expansion of the period of pressure wave oscillations than the corresponding setup utilizing an (HDPE–LDPE) compound short-inline section For example, the period of the first cycle of pressure wave oscillations predicted into the upgraded systems based on an (HDPE–LDPE) compound short-inline section or short-penstock is $T_{\text{HDPE–LDPE}} = 1.340$ s or $T'_{\text{HDPE–LDPE}} = 1.434$ s, respectively; however, the period value corresponding to the original system case is equal to $T_{\text{steel}} = 0.472$ s. This in turn implies that the phase shifts between an (HDPE–LDPE) compound short-inline section or short-penstock-based layout of the upgraded system and their counterpart predicted into the original system are $\phi_{\text{HDPE–LDPE}} = 0.868$ s or $\phi'_{\text{HDPE–LDPE}} = 0.962$ s, respectively. On this point, it may be delineated that the phase shift obtained in this test case

![Figure 7](https://iwaponline.com/aqua/article-pdf/70/2/155/855335/jws0700155.pdf)
is more important than the one deduced, previously, in the first test case. These results suggest that the (HDPE-LDPE) compound short-penstock-based upgraded system provides more important ratios (between the attenuation of up- and down-pressure surge and the phase shift) than the upgraded system utilizing an (HDPE-LDPE) compound short-inline section: \( \alpha^{\text{up}}_{\text{HDPE-LDPE}} = 22.1 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{HDPE-LDPE}} = 10.8 \text{ m/s} \) or \( \alpha^{\text{up}}_{\text{LDPE-LDPE}} = 26.5 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{LDPE-LDPE}} = 14.3 \text{ m/s} \), respectively.

Further interpretations concerning the (HDPE) short-inline section or short-penstock-based setup of the conventional technique-based inline or branching concepts suggest that the attenuation values of the first pressure head peak or crest are \( \delta H^{\text{up}}_{\text{HDPE}} = 25.7 \text{ m} \) and \( \delta H^{\text{down}}_{\text{HDPE}} = 14.0 \text{ m} \) or \( \delta H^{\text{up}}_{\text{LDPE}} = 34.8 \text{ m} \) and \( \delta H^{\text{down}}_{\text{LDPE}} = 22.5 \text{ m} \), respectively. Besides, this conventional technique-based setup of the inline or branching concepts leads to phase shift values: \( \varphi^{\text{HDPE}} = 0.276 \text{ s} \) or \( \varphi^{\text{LDPE}} = 0.488 \text{ s} \), respectively. In other words, the ratios between the attenuation of up- and down-pressure surge and the phase shift obtained using an (HDPE) short-inline section or short-penstock are \( \alpha^{\text{up}}_{\text{HDPE-LDPE}} = 93.0 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{LDPE-LDPE}} = 50.9 \text{ m/s} \) or \( \alpha^{\text{up}}_{\text{LDPE-LDPE}} = 71.3 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{LDPE-LDPE}} = 46.2 \text{ m/s} \), respectively.

Similarly, much lower ratio values are obtained in the upgraded system cases using an (LDPE) short-inline section or short-penstock. In particular, the attenuation values of the first pressure head peak or crest provided by these setups: \( \delta H^{\text{up}}_{\text{LDPE}} = 26.7 \text{ m} \) and \( \delta H^{\text{down}}_{\text{LDPE}} = 14.0 \text{ m} \) or \( \delta H^{\text{up}}_{\text{LDPE}} = 28.8 \text{ m} \) and \( \delta H^{\text{down}}_{\text{LDPE}} = 15.5 \text{ m} \), respectively. Furthermore, these setups of the conventional technique lead to phase shift values equal to \( \varphi^{\text{LDPE}} = 4.148 \text{ s} \) or \( \varphi^{\text{LDPE}} = 2.538 \text{ s} \), respectively. Consequently, the ratios between the attenuation of up- and down-pressure surge and the phase shift obtained using an (LDPE) inline-short-section or short-penstock are \( \alpha^{\text{up}}_{\text{LDPE}} = 6.4 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{LDPE}} = 5.4 \text{ m/s} \) or \( \alpha^{\text{up}}_{\text{LDPE}} = 11.3 \text{ m/s} \) and \( \alpha^{\text{down}}_{\text{LDPE}} = 6.1 \text{ m/s} \), respectively.

Incidentally, the renewed system cases utilizing an HDPE or LDPE main pipe-based renewed system cases lead to a more important reduction of pressure wave magnitude than that involved by the original system case. In this respect, the attenuations of up- and down-pressure surge magnitudes involved by an HDPE or LDPE main pipe are \( \delta H^{\text{up}}_{\text{HDPE-LDPE}} = 7.5 \text{ m} \) and \( \delta H^{\text{down}}_{\text{HDPE-LDPE}} = 6.8 \text{ m} \) or \( \delta H^{\text{up}}_{\text{LDPE-LDPE}} = 4.3 \text{ m} \) and \( \delta H^{\text{down}}_{\text{LDPE-LDPE}} = 5.6 \text{ m} \), respectively. However, the foregoing renewed system
layouts induce significant expansion of the period of the first cycle of pressure wave oscillations, as compared to upgraded system setup based on an (HDPE–LDPE) compound short-penstock. Specifically, the phase shifts between an (HDPE) or (LDPE) main pipe-based layouts of the renewed systems and their counterpart predicted into the original system case are $\phi_{\text{HDPE mainpipe}} = 0.276$ s or $\phi_{\text{LDPE mainpipe}} = 4.148$ s, respectively.

**CONCLUSIONS**

Overall, the present research verified the key advantage of the compound technique-based inline and branching concepts over the conventional technique-based ones, which lies in the trade-off between the attenuation of the first pressure head peak and crest and the period of pressure wave oscillations. In this regard, the upgraded system layout devised upon an (HDPE–LDPE) compound short-penstock-based branching strategy illustrated the best trade-off between the two last parameters. Although this study investigated the case of a single pipe system, extended simulation of pipe networks may be addressed as a perspective to the present study.

**DISCLOSURE STATEMENT**

The author declares that there are no conflicts of interest.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

**REFERENCES**

Aklonis, J. J., MacKnight, W. J. & Shen, M. 1972 *Introduction to Polymer Viscoelasticity*. Wiley-Interscience/John Wiley & Sons, Inc., New York.

Benlla, R. & Triki, A. 2019 Assessment of inline techniques-based water-hammer control strategy in water supply systems. *J. Water Supply Res. Technol. AQUA* 68 (7), 562–572. doi:10.2166/aqua.2019.095.

Bertaglia, G., Ioriatti, M., Valiani, A., Dumbser, M. & Calefﬁ, V. 2018 Numerical methods for hydraulic transients in viscoelastic pipes. *J. Fluids Struct.* 81, 250–254. doi:10.1016/j.jfluidstructs.2018.05.004.

Besharat, M., Tarinejad, R. & Ramos, H. 2015 The effect of water hammer on a confined air pocket towards flow energy storage system. *J. Water Supply Res. Technol. AQUA* 65 (2), 116–126. doi:10.2166/aqua.2015.081.

Boulos, P. F., Karney, B. W., Wood, D. J. & Lingireddy, S. 2005 Hydraulic transient guidelines for protecting water distribution systems. *J. Am. Water Works Assoc.* 97 (5), 111–124. doi:10.1002/j.1551-8833.2005.tb10892.x.

Brinson, H. F. & Brinson, L. C. 2008 *Polymer Engineering Science and Viscoelasticity: An Introduction*. Springer, New York.

Cao, H., Mohareb, M. & Nistor, I. 2020 Finite element for the dynamic analysis of pipes subjected to water hammer. *J. Fluids Struct.* 95, 102845. doi:10.1016/j.jfluidstructs.2019.102845.

Carriço, N., Soares, A. & Covas, D. 2016 Uncertainties of inverse transient modelling with unsteady friction and pipe-wall viscoelasticity. *J. Water Supply Res. Technol. AQUA* 65 (4), 342–353. doi:10.2166/aqua.2016.075.

Chaker, M. A. & Triki, A. 2020a Investigating the branching redesign strategy for surge control in pressurized steel piping systems. *Int. J. Pres. Ves. Pip.* 179, 135–144. doi:10.1016/j.ijpvp.2020.104044.

Chaker, M. A. & Triki, A. 2020b The branching redesign technique used for upgrading steel-pipes-based hydraulic systems: re-examined. *J. Pressure Vessel Technol. ASME* 143 (3), 031302. doi:10.1115/1.14047829.

Chen, T., Ren, Z., Xu, C. & Loxton, R. 2015 Optimal boundary control for water hammer suppression in fluid transmission pipelines. *Comput. Math. Appl.* 69 (4), 275–290. doi:10.1016/j.camwa.2014.11.008.

Covas, D., Stoianov, I., Ramos, H., Graham, N., Maksimovic, C. & Butler, D. 2004 Waterhammer in pressurised polyethylene pipes: conceptual model and experimental analysis. *Urban Water J.* 1 (2), 177–197. doi:10.1080/15730620412331289977.

Du, X. X., Lambert, M. F., Chen, L., Hu, E. J. & Xi, W. 2020 Pipe burst detection, localization, and quantification using the transient pressure damping method. *J. Hydraul. Eng. ASCE* 146 (11), 04020077. doi:10.1061/(ASCE)HY.1943-7900.0001810.

Duan, H. F., Ghidaoui, M. S. & Tung, Y. K. 2000a Energy analysis of viscoelastic effect in pipe fluid transients. *J. Appl. Mech.* 77 (4), 044503. doi:10.1115/1.1400915.

Duan, H. F., Ghidaoui, M., Lee, P. J. & Tung, Y. K. 2000b Unsteady friction and visco-elasticity in pipe fluid transients. *J. Hydraul. Res.* 48 (3), 354–362. doi:10.1080/00221681003726247.
Duan, H. F., Ghidaoui, M. S., Lee, P. J. & Tung, Y. K. 2012 
Relevance of unsteady friction to pipe size and length in pipe 
fluid transients. J. Hydraul. Eng. ASCE 138 (2), 154–166.

Duan, H. F., Che, T. C., Lee, P. J. & Ghidaoui, M. S. 2018 Influence 
of nonlinear turbulent friction on the system frequency 
response in transient pipe flow modelling and analysis. 
J. Hydraul. Res. 56 (4), 451–463. doi:10.1080/00221686.2017. 
1599936.

Duan, H. F., Pan, B., Manli, W., Chen, L., Zheng, F. & Zhang, Y. 
2020 State-of-the-art review on the transient flow modeling 
and utilization for urban water supply system (UWSS) 
management. J. Water Supply Res. Technol. AQUA 
jws2020048. doi:10.2166/aqua.2020.048.

Evangelista, S., Leopardi, A., Pignatelli, R. & De Marinis, G. 2015 
Hydraulic transients in viscoelastic branched pipelines. 
J. Hydraul. Eng. ASCE 141 (8), 04015016. doi:10.1061/ 
(ASCE)HY.1943-7900.0001030.

Ferrante, M. & Capponi, C. 2017 Experimental characterization of 
PVC-O pipes for transient modeling. J. Water Supply Res. 
Technol. AQUA 66 (8), 606–620. doi:10.2166/aqua.2017.060.

Fersi, M. & Triki, A. 2019 Investigation on re-designing strategies 
for water-hammer control in pressurized-piping systems. 
J. Pressure Vessel Technol. ASME 141 (2), 021301. doi:10. 
1115/1.4001436.

Ghidaoui, M. S., Zhao, M., McInnis, D. A. & Axworthy, D. H. 
2005 A review of water hammer theory and practice. Appl. 
Mech. Res. 58 (1), 49–76. doi:10.1115/1.1828050.

Gong, J., Stephens, M. L., Lambert, M. F., Zecchin, A. C. & 
Simpson, A. R. 2018 Pressure surge suppression using a 
metallic-plastic-metallic pipe configuration. J. Hydraul. Eng. 
ASCE 144 (6), 04018025. doi:10.1061/(ASCE)HY.1943- 
7900.0001468.

Jung, B. S. & Karney, B. 2009 Systematic surge protection for 
worst-case transient loadings in water distribution systems. 
J. Hydraul. Eng. ASCE 135 (3), 218–223. doi:10.1061/(ASCE) 
0733-9429(2009)135:3(218).

Jung, B. S., Karney, B. W., Boulos, P. F. & Wood, D. J. 2007 The 
need for comprehensive transient analysis of distribution 
systems. J. Am. Water Works Assoc. 99 (1), 112–123. doi:10. 
1002/j.1551-8833.2007.tb07851.x.

Jung, B. S., Boulos, P. F., Wood, D. J. & Howie, C. 2008 Accurate 
demand modeling for surge analysis. In: World 
Environmental and Water Resources Congress, May 12–16, 
2008, Honolulu, Hawaii. doi:10.1061/40976(316)490.

Jung, B. S., Muleta, M. & Boulos, P. F. 2009 Multi-objective design 
of transient network models. In: World Environmental and 
Water Resources Congress, May 17–21, 2009, Kansas City, 
MI. doi:10.1061/41036(342)577.

Keramat, A. & Haghighi, A. 2014 Straightforward transient-based 
approach for the creep function determination in viscoelastic 
pipes. J. Hydraul. Eng. ASCE 140 (12), 04014058. doi:10. 
1061/(ASCE)HY.1943-7900.0000929.

Kubrak, M. & Kodura, A. 2020 Water hammer phenomenon in 
pipeline with inserted flexible tube. J. Hydraul. Eng. ASCE 
146 (2), 04019054. doi:10.1061/(ASCE)HY.1943-7900. 
0000571.

Lashkarbolok, M. & Tijsseeling, A. S. 2020 Numerical simulation of 
water-hammer in tapered pipes using an implicit least- 
squares approach. Int. J. Pres. Vip. 187, 104161. doi:10. 
1016/j.ipvpp.2020.104161.

Massouh, F. & Comolto, R. 1984 Étude d’un système anti-bélier en 
ligne (Study of a water-hammer protection system in line). La 
Houille Blanche 5, 355–362. doi:10.1051/lhb/1984025.

Mitosek, M. & Szymkiewicz, R. 2012 Wave damping and 
smoothing in the unsteady pipe flow. J. Hydraul. Eng. ASCE 
138 (7), 619–628. doi:10.1061/(ASCE)HY.1943-7900.0000571.

Pan, B., Duan, H. F., Meniconi, S., Urbanowicz, K., Che, T. C. & 
Brunone, B. 2020 Multistage frequency-domain transient- 
based method for the analysis of viscoelastic parameters of 
plastic pipes. J. Hydraul. Eng. ASCE 146 (3), 04019068. 
doi:10.1061/(ASCE)HY.1943-7900.0001700.

Pan, B., Duan, H. F., Meniconi, S. & Brunone, B. 2021 FRF-based 
transient wave analysis for the viscoelastic parameters 
identification and leak detection in water-filled plastic pipes. 
Mech. Syst. Signal Process. 146, 107056. doi:10.1016/j. 
ymssp.2020.107056.

Pezzinga, G. & Cinzia Santoro, V. 2020 Shock-capturing 
characteristics models for transient vaporous caviation in 
pipe flow. J. Hydraul. Eng. ASCE 146 (11), 04020075. doi: 
10.1061/(ASCE)HY.1943-7900.0001811.

Pezzinga, G. & Scandura, P. 1995 Unsteady flow in installations with 
polymeric additional pipe. J. Hydraul. Eng. ASCE 121 (11), 
802–811. doi:10.1061/(ASCE)0733-9429(1995)121:11(802).

Ramos, H., Covas, D., Borda, A. & Loureiro, D. 2004 Surge 
damping analysis in pipe systems: modelling and 
experiments. J. Hydraul. Res. 42 (4), 413–425. doi:10.1080/ 
00221686.2004.9641209.

Seog-Jung, B. & Karney, B. W. 2009 Systematic surge protection for 
worst-case transient loadings in water distribution systems. 
J. Hydraul. Eng. ASCE 135 (3), 218–223. doi:10.1061/( 
ASCE)0733-9429(2009)135:3(218).

Thorley, A. R. D. 2004 Fluid Transients in Pipeline Systems, 2nd 
edn. D&L George, Herts.

Trabelsi, M. & Triki, A. 2019 Dual control technique for mitigating 
water-hammer phenomenon in pressurized steel-piping 
systems. Int. J. Pres. Ves. Pip. 172, 397–413. doi:10.1016/j. 
ijpvp.2019.04.011.

Trabelsi, M. & Triki, A. 2020 Exploring the performances of the 
dual technique-based water-hammer redesign strategy in 
water-supply systems. J. Water Supply Res. Technol. AQUA 
69 (1), 30–43. doi:10.2166/aqua.2017.073.

Triki, A. 2016 Water-hammer control in pressurized-pipe flow 
using an in-line polymeric short-section. Acta Mech. 
227 (3), 777–793. doi:10.1007/s00070-015-1493-13.

Triki, A. 2017 Water-hammer control in pressurized-pipe flow 
using a branched polymeric penstock. J. Pipe Sys. Eng. Pract. 
ASCE 8 (4), 04017024. doi:10.1061/(ASCE)PS.1949-1204. 
0000277.
Triki, A. 2018a Further investigation on water-hammer control inline strategy in water-supply systems. J. Water Supply Res. Technol. AQUA 67 (1), 30–43. doi:10.2166/aqua.2017.073.

Triki, A. 2018b Dual-technique based inline design strategy for water-hammer control in pressurized-pipe flow. Acta Mech. 229 (5), 2019–2039. doi:10.1007/s00707-017-2085-z.

Triki, A. & Chaker, M. A. 2019 Compound technique-based inline design strategy for water-hammer control in steel pressurized-piping systems. Int. J. Pres. Ves. Pip. 169, 188–203. doi:10.1016/j.ijpvp.2018.12.001.

Triki, A. & Fersi, M. 2018 Further investigation on the water-hammer control branching strategy in pressurized steel-piping systems. Int. J. Pres. Ves. Pip. 165, 135–144. doi:10.1016/j.ijpvp.2018.06.002.

Vitkovsky, J. P., Lambert, M. F., Simpson, A. R. & Bergant, A. 2000 Advances in unsteady friction modelling in transient pipe flow. In: 8th International Conference on Pressure Surges: Safe Design and Operation of Industrial Pipe Systems, Vol. 39. BHR Group Conference Series Publication, The Hague, pp. 471–482.

Walters, T. W. & Leishear, R. A. 2018 When the Joukowsky equation does not predict maximum water hammer pressure.

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