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 nonlinear 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 frame-
work. Accordingly, this research aims at gaining further
insight into the water hammer control topic by comprehen-
sively assessing and comparing the capacities of the
compound technique-based inline and branching
strategies in terms of the trade-off (between the magni-
tude-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. Additional-
ly, 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 approxi-
mating the flow parameters is briefly outlined.

METHODOLOGY

From a computational point of view, different approaches
can be used for hydraulic transient analysis, including sim-
plified approaches used for extreme pressure surge
magnitude estimation (such as the Joukowski law for
rapid maneuvers, and the Michaud formula for slow man-
euvers), 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;
Ghidaouï et al. 2005; Wood et al. 2005; Duan et al.
2010b; Duan et al. 2012; 2018; 2020; Carriço 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 fol-
lows (detailed derivations are reported in Covas et al. 2004
and Triki 2017, 2018a, 2018b):

$$\frac{\partial H}{\partial t} + \frac{a_0^2}{gA} \frac{\partial Q}{\partial x} + 2 \frac{a_0^2}{g} \frac{\partial E}{\partial t} = 0$$

\[ \frac{1}{A} \frac{\partial Q}{\partial t} + g \frac{\partial H}{\partial x} + g(h_i + h_f) = 0 \]

where \( H \) = pressure head; \( Q \) = discharge; \( A \) = pipe
section area; \( g \) = gravity acceleration; \( a_0 = \sqrt{K/\rho/1 + \xi(D/e)K_0} \) = elastic-wave-speed; \( K \) = bulk
elasticity modulus of the fluid \( (K = 2.19 \text{ GPa, for water}); \rho = \text{mass density of the fluid}\ (\rho = 999 \text{ kg/m}^3, \text{for water}); \xi = \text{dimensionless parameter describing pipe constraint condition} \) \( (\xi = 1.04, \text{for thin-wall elastic pipes (Wylie & Streeter 1993))}); \( I_0 \) = elastic creep compliance of the pipe-wall material; \( h_i \) = quasi-steady pressure head-loss component per unit
length, computed from the Colebrook–White \( h_i = fQ/Q/(2DA)^2 \) and the Hagen–Poiseille \( h_i = 32\nu/Q/gD^2A \) formulas, for turbulent and laminar
flow, respectively; \( f = \text{Darcy–Weisbach friction factor}; \nu = \text{fluid kinematic viscosity}; D = \text{inner diameter}; e = \text{pipe-wall thickness}; x = \text{distance along the pipe centerline}; \text{and } t = \text{time}.\)

The unsteady friction component \( h_f \) is expressed refer-
ing to the Vitkovsky et al. (2000) formulation:

$$h_f = \frac{k_v}{gA} \left( \frac{\partial Q}{\partial t} + a_0 \text{Sgn}(Q) \left| \frac{\partial Q}{\partial x} \right| \right)$$

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):

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

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

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
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 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):

\[
C^{ij} = \frac{\partial H^j}{\partial t} + \frac{a_0^j}{g} \frac{\partial Q^j}{\partial t} + 2a_0^j \left( \frac{\partial v^j}{\partial t} \right) + a_0^j q^j = 0 \quad \text{along} \quad \Delta t = \frac{c_s^j}{a_0^j}
\]

\[
\Delta v^j = a_0^j \frac{c_s^j}{\Delta t}
\]

where \( j \) = pipe number (1 \( \leq j \leq np \)); \( i \) = section index (1 \( \leq i \leq n_i^j \)), \( n_i^j \) = 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; Pezzeinga & 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:

\[
V^j_t = V_t^{j-2\Delta t} + \left[ \psi(Q^i_t - Q_t^{ai}) - (1 - \psi)(Q_t^{j-2\Delta t} - Q_t^{j-2\Delta t}) \right] \\
\times 2 \times \Delta t
\]

where \( Q \) and \( Q_a \) = average discharges at the up- and downstream 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 isothermal evolution of the cavity reads:

\[
V^j_t \times (H_t^j - z_t^j - H_v) = (H_0 - z_i^j - H_v) \times a_0 \times A \times \Delta t
\]

in which \( H_0 \) = reference pressure head; \( a_0 \) = void-fraction at \( H_0 \); \( z_i \) = pipe elevation; and \( H_v \) = gauge vapor pressure head of the liquid (\( H_v = -10.2 \) m for water).

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

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

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

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

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

$$\Delta x^j = \frac{c_j \Delta t}{c_r}$$  \hspace{1cm} (10)

where $c_j$ is the Courant number associated with the $j$th 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 \{${q_0}^{\text{HDPE}} = 404.9$ m$^3$/s; length: $L = 271.8$ m; pipe-wall thickness: $e = 6.25$ mm; and diameter: $D = 50.6$ mm\}; and the coefficients of the Kelvin–Voigt formulation of HDPE material are listed in Table 1 (Keramat & Haghighi 2014). The initial steady-state discharge and pressure head at the upstream reservoir are $q_0 = 1.008$ L/s and $h_0^{p} = 35$ 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 $\Delta t = 0.016s$ 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.

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 $\Delta H^{\text{1D-EWH Eqs}} = 19.5$ m. Likewise, the theoretical period values computed for the HDPE or LDPE main-piping systems (i.e. $T_1^{\text{th}} = 1.33$ 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. $T_1^{\text{observed}} = 3.21s$ and $T_1^{\text{1D-EWH Eqs}} = 3.19$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

<table>
<thead>
<tr>
<th>Time-steps (s)</th>
<th>0.016</th>
<th>0.008</th>
<th>0.004</th>
<th>0.002</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{\text{up-surge}}$ (m)</td>
<td>19.5</td>
<td>19.5</td>
<td>19.4</td>
<td>19.5</td>
</tr>
</tbody>
</table>
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: \( \Delta H^{+/-} = |H_{\max}^{\text{a}} - H_{\text{d}}| \); (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 \( H_{\text{Reservoir}} = 45 \text{ m} \); before a transient event caused by the abrupt and full closure of the downstream valve. Such an event may be described as follows:

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

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: \( c_{\text{compound}}^{\text{sub-short-section}} = 2.5 \text{ m} \) and \( c_{\text{compound}}^{\text{short-section}} = 53.2 \text{ mm} \). 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: \( c_{\text{conventional}}^{\text{short-section}} = 5 \text{ m} \) and \( c_{\text{conventional}}^{\text{short-section}} = 53.2 \text{ mm} \).

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...
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 | HDPE | LDPE | HDPE | LDPE | Inline–LDPE | Branching–LDPE |
| $T_1$ (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: $\Delta H_{\text{steel}} = 40.6 \text{ m}$ and $\Delta H_{\text{steel}} = 40.6 \text{ m}$, 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 $\delta H_{\text{HDPE–LDPE}} = 5.4 \text{ m}$ and $\delta H_{\text{HDPE–LDPE}} = 19.5 \text{ m}$ or $\delta H_{\text{HDPE–LDPE}} = 16.8 \text{ m}$ and $\delta H_{\text{HDPE–LDPE}} = 18.6 \text{ m}$, 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 $T_{\text{HDPE–LDPE}} = 1.026 \text{ s}$ or $T_{\text{HDPE–LDPE}} = 0.894 \text{ s}$, respectively; while the corresponding period, involved by the original system case, is equal to: $T_{\text{steel}} = 0.42 \text{ s}$. 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 $\phi_{\text{HDPE–LDPE}} = 0.606\text{s}$ or $\phi_{\text{HDPE–LDPE}} = 0.564\text{s}$, 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: \[ \alpha_{\text{HDPE-LDPE}}^+ = 9.0 \text{ m/s} \text{ or } \alpha_{\text{HDPE-LDPE}}^- = 20.2 \text{ m/s} \]
and \[ \alpha_{\text{HDPE-LDPE}}^+ = 29.7 \text{ m/s} \text{ or } \alpha_{\text{HDPE-LDPE}}^- = 33.0 \text{ m/s} \], 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 \[ \delta H_{\text{HDPE}}^+ = 20.5 \text{ m and } \delta H_{\text{LDPE}}^- = 22.1 \text{ m} \] 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-penstock-based upgraded systems are \( \alpha_{\text{HDPE}}^+ = 72.2 \text{ m/s} \text{ or } \alpha_{\text{HDPE}}^- = 86.9 \text{ m/s} \) and \( \alpha_{\text{LDPE}}^+ = 27.4 \text{ m/s} \text{ or } \alpha_{\text{LDPE}}^- = 43.7 \text{ m/s} \), 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 \( z_u = 2.03 \) m above the downstream pipe axis. The initial flow velocity in the piping system is: \( v_0 = 1.04 \) m/s, corresponding to a constant pressure head \( H_T^0 = 21.4 \) 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:

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

(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: \( l_{\text{compound short-section}} = 5 \) m and \( d_{\text{compound sub-short-section}} = 53.2 \) 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: \( l_{\text{conventional short-section}} = 10 \) m and \( d_{\text{conventional short-section}} = 53.2 \) 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. $H_{\text{steel}}^{\text{min}} = -10.2 \text{ m}$); and, subsequently, rises to $H_{\text{steel}}^{\text{max}} = 63.7 \text{ m}$, 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 $\Delta H_{\text{steel}} = 41.7 \text{ m}$ and $\Delta H_{\text{steel}} = 32.2 \text{ m}$, 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 \{$\delta H_{\text{HDPE–LDPE}} = 19.2 \text{ m}$ and $\delta H_{\text{HDPE–LDPE}} = 9.4 \text{ m}$\} or \{$\delta' H_{\text{HDPE–LDPE}} = 25.5 \text{ m}$ and $\delta' H_{\text{HDPE–LDPE}} = 13.8 \text{ m}$\}, 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 $T_{\text{HDPE–LDPE}} = 1.340 \text{ s}$ or $T'_{\text{HDPE–LDPE}} = 1.434 \text{ s}$, respectively; however, the period value corresponding to the original system case is equal to $T_{\text{steel}} = 0.472 \text{ s}$. 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 $\phi_{\text{HDPE–LDPE}} = 0.868 \text{ s}$ or $\phi'_{\text{HDPE–LDPE}} = 0.962 \text{ s}$, respectively. On this point, it may be delineated that the phase shift obtained in this test case
Table 4 | Characteristics of the pressure waves in Figure 7

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Steel main pipe</th>
<th>Plastic main pipe</th>
<th>Conventional technique</th>
<th>Compound technique</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>T₁ (s)</td>
<td>H₀ (m)</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>0.472</td>
<td>4.351</td>
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<td>–2.2</td>
<td>–2.2</td>
</tr>
</tbody>
</table>

Figure 7 | Magnitudes of up- and down-pressure surges versus the period of the first cycle of wave oscillations.

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: \( \alpha_{\text{HDPE-LDPE}}^{\text{up}} = 22.1 \text{ m/s} \) and \( \alpha_{\text{HDPE-LDPE}}^{\text{down}} = 10.8 \text{ m/s} \) or \( \alpha_{\text{HDPE-LDPE}}^{\text{up}} = 26.5 \text{ m/s} \) and \( \alpha_{\text{HDPE-LDPE}}^{\text{down}} = 14.3 \text{ m/s} \), 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 \( \delta H_{\text{HDPE}}^{\text{up}} = 25.7 \text{ m} \) and \( \delta H_{\text{HDPE}}^{\text{down}} = 14.0 \text{ m} \) or \( \delta H_{\text{HDPE}}^{\text{up}} = 34.8 \text{ m} \) and \( \delta H_{\text{HDPE}}^{\text{down}} = 22.5 \text{ m} \), 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 \( \varphi'_{\text{HDPE}} = 0.488 \text{ s} \), 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 \( \left\{ \alpha_{\text{HDPE}}^{\text{up}} = 93.0 \text{ m/s} \right\} \) and \( \left\{ \alpha_{\text{HDPE}}^{\text{down}} = 50.9 \text{ m/s} \right\} \) or \( \left\{ \alpha_{\text{HDPE}}' = 71.5 \text{ m/s} \right\} \) and \( \left\{ \alpha_{\text{HDPE}}' = 46.2 \text{ m/s} \right\} \), 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: \( \left\{ \delta H_{\text{LDPE}}^{\text{up}} = 26.7 \text{ m} \right\} \) and \( \left\{ \delta H_{\text{LDPE}}^{\text{down}} = 14.0 \text{ m} \right\} \) or \( \left\{ \delta H_{\text{LDPE}}^{\text{up}} = 28.8 \text{ m} \right\} \) and \( \left\{ \delta H_{\text{LDPE}}^{\text{down}} = 15.5 \text{ m} \right\} \), 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 \( \left\{ \alpha_{\text{LDPE}}^{\text{up}} = 6.4 \text{ m/s} \right\} \) and \( \left\{ \alpha_{\text{LDPE}}^{\text{down}} = 5.4 \text{ m/s} \right\} \) or \( \left\{ \alpha_{\text{LDPE}}' = 11.3 \text{ m/s} \right\} \) and \( \left\{ \alpha_{\text{LDPE}}' = 6.1 \text{ m/s} \right\} \), 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 \( \left\{ \delta H_{\text{mainpipe}}^{\text{HDPE}} = 7.5 \text{ m} \right\} \) and \( \left\{ \delta H_{\text{mainpipe}}^{\text{LDPE}} = 6.8 \text{ m} \right\} \) or \( \left\{ \delta H_{\text{mainpipe}}^{\text{LDPE}} = 4.3 \text{ m} \right\} \) and \( \left\{ \delta H_{\text{mainpipe}}^{\text{LDPE}} = 3.6 \text{ m} \right\} \), 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 pound short-penstock. Specifically to the present study.

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.

CONCLUSIONS

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


BenIlfa, R. & Triki, A. 2019 Assessment of inline techniques-based water-hammer control strategy in water supply systems.


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


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