Assessment of inline technique-based water hammer control strategy in water supply systems

Ridha Ben Iffa and Ali Triki

ABSTRACT

This article discusses and compares the effectiveness of the compound and dual technique-based inline strategy used to upgrade existing steel pipe-based water supply systems. Basically, these techniques are based on splitting the single inline short section, used in the conventional technique, into a couple of two sub-short sections made of two distinct plastic material types: high- and low-density polyethylene (HDPE) and (LDPE). The 1D unconventional water hammer solver based on the method of characteristics was used for numerical computations. Results evidenced that the specific setup of the compound technique based on (HDPE-LDPE) sub-short sections (where the former sub-short section is attached to the hydraulic parts, while the latter is attached to the main steel pipe) is the most prominent configuration providing an acceptable trade-off between attenuation of pressure head surge, and limitation of excessive wave oscillation period spreading. Furthermore, this compound technique setup allowed more important pressure head peak (or crest) attenuation as compared with the dual technique based on (LDPE-LDPE) sub-short sections; while inducing about similar values of wave oscillation period spreading.

Key words | compound, design, dual, HDPE/LDPE material, water hammer

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INTRODUCTION

Water supply systems unavoidably face the water hammer phenomenon due to either normal setting processes (e.g., opening/closing of valves, starting/stopping of pumps, and variations in inflow or outflow) or accidental events (e.g., improper setting, hydraulic parts or machinery breakdowns). This phenomenon displays a series of positive and negative pressure waves (i.e., unsteady pressure fluctuations), which may be large enough to induce severe conditions such as excessive noise, fatigue, stretch, or rupture of the pipe wall and even cause major problems, potentially risky for operators or users (Bergant *et al.* 2006). Consequently, the control of such a phenomenon in water supply systems constitutes a major concern for design engineers and pipe system managers to ensure safe and efficient operation of these utilities and to provide the adequate service level to users.

In this regard, water hammer control strategies typically include: (i) change of pipe pressure class or material; (ii) design of optimal operational procedures; and (iii) installation of surge control devices (e.g., automatic control valves, surge tanks, and air chambers) (Besharat *et al.* 2015; Coronado-Hernández *et al.* 2019; Deyou *et al.* 2019; Wan *et al.* 2019). Commonly, a combination of these strategies are employed by designers to attenuate water hammer surges to an acceptable extent; however, the cumulative effect of different types of control devices may reversely affect the water hammer courses, due to substantial inconsistency between the embedded devices.

Alternatively to classical design measures and based on the ability of plastic materials to attenuate high- and low-transient pressure, recent researches have entailed the

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inline (which is based on the replacement of a short section of the sensitive zone of the main pipe by another made of plastic material) and branching strategies (which is based on adding a branched plastic short section at the sensitive zone of the main pipe) in order to upgrade existing steel piping systems (Massouh & Comolet 1984; Ghilardi & Paoletti 1986; Pezzinga & Scandura 1995; Triki 2016, 2017, 2018a, 2018b; Triki & Fersi 2018; Fersi & Triki 2019; Triki & Chaker 2019; Trabelsi & Triki 2019a, 2019b). In particular, recent investigations conducted by these authors recognized that the inline strategy could serve as an effective tool for attenuating water hammer upsurges and downsurges in water supply systems; however, this strategy, due to its conventional implementation technique, induced large spreading of pressure wave oscillation period, which may critically increase the admissible critical time for valve closure. The materials demonstrated by the authors included high- and low-density polyethylene (HDPE) and (LDPE). In exact terms, the authors pointed out that the use of a (LDPE) polymeric material type for the replaced short section allowed more important pressure head attenuation than the (HDPE) polymeric material type; whereas the former material type induced a long period of pressure wave oscillation compared with the latter material type. In fact, the preceding drawback of the inline strategy is mainly attributed to the dependence between the reduced modulus of the short section material used, which results in pressure head attenuation, and the viscoelastic mechanical behavior of the short section, which may amplify the radial strain magnitude due to a retarded hydraulic transient response (Brinson & Brinson 2008).

Alternatively, to address the inline strategy drawback concerning its conventional technique, Triki (2018b) proposed a dual technique-based inline strategy. This technique is based on replacing the short sections of the main piping system, each upstream of its connections to hydraulic parts, by other ones made of (HDPE) or (LDPE) polymeric materials. In particular, the author proved that the particular dual technique configuration utilizing an upstream and downstream (LDPE) sub short-section resulted in a significant reduction of pressure head magnitude and identified an even better alternative than the conventional technique-based inline strategy in terms of limitation of pressure wave oscillation period spreading.

Subsequently, a second alternative was proposed by Triki & Chaker (2019), named henceforth compound technique, based on splitting the single short section used in the conventional technique into a couple of 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 and the low pressure wave oscillation period spreading capacities provided by the (LDPE) and (HDPE) polymeric material types, respectively. The authors demonstrated that the compound technique based on (HDPE-LDPE) sub-short sections (where the former sub-short section is attached to the hydraulic parts, while the latter is attached to the main steel pipe) is the most prominent configuration providing an acceptable trade-off between attenuation of pressure head magnitude and limitation of excessive spreading of wave oscillation period.

In summary, previous investigations on dual and compound technique-based inline strategy illustrated significant improvements of the skills of the conventional technique. However, as discussed above, the conflicts between the pressure head amortization and spreading of pressure wave oscillation period factors, concerning these two techniques, is a challenging issue that deserves investigation. Accordingly, this research addresses further insight for the inline strategy concept by comprehensively assessing and comparing the effectiveness of the dual and compound technique-based inline strategy with regard to the two foregoing factors.

In the following sections, first the methodology used for modeling transient flow is briefly described. Second, the reliability of the compound and dual techniques within water hammer up- and down-initiated surge scenarios is assessed. Lastly, concluding remarks are presented.

(1-D) UNCONVENTIONAL WATER-HAMMER SOLVER

The flow parameters involved by fast transient events into plastic pipes may be described using the one-dimensional (1D) water hammer model combined with the Kelvin–Voigt (Aklonis *et al.* 1972) and Vitkovsky *et al.* (2000) formulations. Specifically, this model was validated in previous works of the authors (e.g., Triki 2017, 2018a, 2018b). This model may be expressed as follows:

$$\begin{cases} \dfrac{\partial H}{\partial t} + \dfrac{a_0^2}{gA}\dfrac{\partial Q}{\partial x} + 2\dfrac{a_0^2}{g}\dfrac{d\varepsilon}{dt} = 0 \\ \dfrac{1}{A}\dfrac{\partial Q}{\partial t} + g\dfrac{\partial H}{\partial x} + g(h_{f_s} + h_{f_u}) = 0 \end{cases} \tag{1}$$

wherein H is instantaneous pressure head; Q is discharge; A is cross-sectional area of the pipe; g is gravity acceleration; a_0 is wave speed; ε is radial strain, which may be described referring to the linear viscoelastic Kelvin–Voigt model (Aklonis *et al.* 1972) $\varepsilon(x, t) = \sum_{k=1}^{N_{kv}} \varepsilon_k = \sum_{k=1}^{N_{kv}} \rho g \frac{\alpha D}{2e} \int_0^s [H(x, t) - H_0(x)](J_k/\tau_k)e^{-(s/\tau_k)}ds$, in which, J_0 is elastic creep compliance, J_k and τ_k $(k = 0 \cdots n_{kv})$ is creep compliance and the retardation time coefficients associated with k^{th} Kelvin–Voigt element, respectively, n_{kv} is number of Kelvin–Voigt elements; h_{f_s} is quasi-steady head-loss component per unit length, which may be determined using the Colebrook–White $(h_{f_s} = RQ|Q|)$ or the Hagen–Poiseuille rules $(h_{f_s} = 32\nu'|Q|/(gD^2A))$, for turbulent or laminar flow regimes, respectively; h_{f_u} is unsteady friction loss, which may be approximated according to the Vitkovsky *et al.* (2000) formula $h_{f_u} = (k_v/gA)\{(\partial Q/\partial t) + a_0\, sgn(Q)|\partial Q/\partial x|\}$, in which, $k_v = 0.03$ is Vitkovsky decay coefficient, $sgn(Q) = +1$ or -1 for $Q \geq 0$ or $Q \prec 0$, respectively; x and t are coordinates along the pipe axis and time, respectively.

The numerical solution of the water hammer model (1) may be established using the method of characteristics based on a fixed time step mesh (FTSG-MOC). This numerical procedure follows from the concept presented in Wylie & Streeter (1993), Triki (2017, 2018a, 2018b), Triki & Chaker (2019), and Trabelsi & Triki (2019a, 2019b).

Briefly, the discretization of Equation (1) using the FTSG-MOC leads to the following solution along characteristic lines:

$$\mathbf{C}^{\pm}: \begin{cases} Q_{i,t}^j = c_p^j - c_{a-}^j H_{i,t}^j \\ Q_{i,t}^j = c_n^j + c_{a+}^j H_{i,t}^j \end{cases} \text{along } \frac{\Delta x^j}{\Delta t} = \pm \frac{a_0^j}{c_{\mathrm{r}}^j} \tag{2}$$

wherein $c_p^j = (Q_{i-1,t-1}^j + (1/B^j)\, H_{i-1,t-\Delta t}^j + c''^j_{p1} + c'''^j_{p1})/(1 + c'^j_p + c''^j_{p2} + c'''^j_{p2})$; $B = a_0/(gA)$; $c_n^j = (Q_{i+1,t-1}^j + (1/B^j)H_{i+1,t-\Delta t}^j + c''_{n1} + c'''_{n1})/(1 + c'^j_n + c''^j_{n2})$; $c_{a+}^j = 1 + c'''^j_{p2}/(B^j(1 + c'^j_{p2} + c''^j_{p2}))$; $c'^j_p = R^j \Delta t|Q_{i-1,t-1}^j|$; $c'^j_n = R^j \Delta t|q_{i+1,t-1}^j|$; $c''^j_{p1} = k_v \theta Q_{i,t-1}^j - k_v(1-\theta)(Q_{i-1,t-1}^j - Q_{i-1,t-2}^j) - k_v\, sgn(Q_{i-1,t-1}^j)(Q_{i,t-1}^j - Q_{i-1,t-1}^j)$; $c''^j_{n_1} = k_v \theta Q_{i,t-1}^j - k_v(1-\theta)(Q_{i+1,t-1}^j - Q_{i+1,t-2}^j) - k_v sgn(Q_{i+1,t-1}^j)(Q_{i,t-1}^j - Q_{i+1,t-1}^j)$; $c'''^j_{p_1} = -c'''^j_{n_1} = -2a_0^j A^j \Delta t \sum_{k=1}^{n_{kv}} [\varepsilon_k^j(x,t)]$; $c'''^j_{p_2} = c'''^j_{n_2} = 2a_0^j A^j c_0 \gamma \sum_{k=1}^{n_{kv}} J_k^j(1 - e^{-(\Delta t/\tau_k)})$; $\varepsilon_{k,i,t-\Delta t}^j = J_k^j c_0\{[H_{i,t-\Delta t}^j - H_{i,0}^j] - e^{-(\Delta t/\tau_k)}$ $[H_{i,t-2\Delta t}^j - H_{i,0}^j] - \tau_k(1 - e^{-(\Delta t/\tau_k)})[H_{i,t-\Delta t}^j - H_{i,t-2\Delta t}^j]/\Delta t\}e^{-(\Delta t/\tau_k)}$ $\varepsilon_{k,i,t-2\Delta t}$ $c''^j_{p_2} = c''^j_{n_2} = k_v\theta$ $(\theta = 1$ is a relaxation coefficient); $R^j = f^j/2D^jA^j$; $c_0 = \alpha\gamma D^j/2e^j$; c_{r}^j is Courant number; j is pipe number $(1 \leq j \leq np)$; i is section number of the j^{th} pipe $(1 \leq i \leq n_s^j)$; n_s^j is number of sections of the j^{th} pipe; np is number of pipes; Δt and Δx are time step and space step increments, respectively.

It is worth noting that Equation (2) addresses a single-phase flow solution. To determine the numerical solution associated with the cavitating flow regime, the discrete gas cavity model may be adopted (Wylie & Streeter 1993).

Accordingly, each cavity volume may be discretized using the FTSG-MOC as follows:

$$\begin{aligned} \forall_{gi,t} = \forall_{gi,t-2\Delta t} + [\psi(Q_{di,t} - Q_{ui,t}) \\ - (1-\psi)(Q_{di,t-2\Delta t} - Q_{ui,t-2\Delta t})]\, 2\Delta t \end{aligned} \tag{3}$$

wherein $\forall_{gi,t}$ and $\forall_{gi,t-2\Delta t}$ are discrete cavity volumes at the current time step and at $2 \times \Delta t$ time steps earlier, respectively; Q_u and Q_d are discharges, computed at either side of the cavity; and ψ is weighting factor, chosen in the $0.5 \leq \psi \leq 1$ range (Wylie & Streeter 1993).

Additionally, the perfect gas law applied for an isothermal evolution of gas cavities leads to:

$$\forall_{gi,t}(H_{i,t} - z_i - H_g) = (H_0 - z_0 - H_g)\alpha_0 A \Delta x \tag{4}$$

wherein H_0 and H_g are reference and gauge pressure head values ($H_g = -10.29$ m, for water), respectively; α_0 is void fraction at H_0; and z_i is pipe elevation.

Incidentally, the cavity collapses inasmuch as $\forall_{gi,t}^j \prec 0$. In such a case, the single-phase flow is re-established and the (1D) water hammer solution (Equation (2)) is valid again.

Finally, the hydraulic parameters at the inline connection may be expressed under assumptions of no flow storage and common hydraulic grade-line elevation (Wylie & Streeter 1993) as follows:

$$Q^{j-1}_{|x=L} = Q^{j}_{|x=0} \text{ and } H^{j-1}_{|x=L} = H^{j}_{|x=0} \tag{5}$$

APPLICATION SETUP RESULTS AND DISCUSSION

To assess the performances of the (HDPE-LDPE) setup-based compound technique and (LDPE-LDPE) setup-based dual technique, two scenarios including up- and down-initiated surge are examined in this section. For comparison purposes, the results associated with the inline or branching strategies using the conventional technique are also addressed (Triki 2017, 2018a). Furthermore, in order to ensure a consistent comparison between the different protection techniques, with regard to the employed plastic material volume, the utilized (sub) short sections lengths and diameters are linked as follows:

$$\begin{aligned} l^{\text{dual}}_{\text{sub short-section}} &= l^{\text{compound}}_{\text{sub short-section}} \\ &= l^{\text{conventional}}_{\text{short-section}}/2 \text{ and } d^{\text{dual}}_{\text{sub short-section}} \\ &= d^{\text{compound}}_{\text{sub short-section}} = d^{\text{conventional}}_{\text{short-section}} \end{aligned} \tag{6}$$

Additionally, several indicators are used in the following to assess different attributes of the compound technique upon the dual one or the conventional technique-based inline and branching strategies. For example: (i) the attenuation of up- or down-pressure head surge performed by the protected system case based on the compound technique as compared with that involved in the original system case: $\delta H^{\text{Steel}}_{\text{up-surge/down-surge}} = H^{\text{Steel}}_{\text{max/min}} - H^{\text{compound}}_{\text{max/min}}$; (ii) the attenuation ratio of pressure head magnitude involved in the compound technique-based protected system case as compared with the original system case: $\eta H^{\text{Steel}}_{\text{up-surge/down-surge}} = \Delta H^{(\text{HDPE}-\text{LDPE})-\text{compound}}_{\text{max/min}} / \Delta H^{\text{Steel}}_{\text{max/min}}$; (iii) the phase-shift between the first cycle of pressure wave oscillations involved in the compound technique case as compared with the original system case: $\delta T^{\text{Steel}}_{1} = (T^{(\text{HDPE}-\text{LDPE})\text{-compound}}_{1} - T^{\text{Steel}}_{1})$; and (iv) the phase-shift ratio between the compound technique and the original system: $\eta T^{\text{Steel}}_{1} = (T^{(\text{HDPE}-\text{LDPE})-\text{compound}}_{1} - T^{\text{Steel}}_{1})/T^{\text{Steel}}_{1}$. Similar rules are used to compare the compound technique and the dual or conventional technique.

The input parameters associated with the FTSG-MOC procedure are: time step $\Delta t = 0.017$ s; Courant numbers: $c^{\text{steel}-\text{pipe}}_{\text{r}} = 0.9841$ and $c^{\text{plastic short-section}}_{\text{r}} = 1$, corresponding to the steel main pipe and the plastic short section; and $\psi = 0.5$. The Kelvin–Voigt characteristics of the (HDPE) and (LDPE) materials are: $\{J_k[\text{GPa}^{-1}]; \tau_k[\text{s}]\}^{\text{HDPE}}_{k=0-5} = \{0.8032; -/1.057; 0.05/1.054; 0.5/0.905; 1.5/0.262; 5/0.746; 10\}$; and $\{J_k[\text{GPa}^{-1}]; \tau_k[\text{s}]\}^{\text{LDPE}}_{k=0-3} = \{2.083; -/7.54; 0.00089/10.46; 0.022/12.37; 1.864\}$, respectively (Keramat & Haghighi 2014).

Case 1: Upsurge-initiated water hammer event

The case study concerns a reservoir steel pipe valve system, sketched in Figure 1(a). The steel pipe characteristics are: $L = 100$ m; $D = 53.2$ mm; $e = 3.35$ mm; $a^{\text{Steel}}_{0} = 1369.7$ m/s and $J^{\text{Steel}}_{0} = 0.0049$ GPa^{-1}. Initially, the outflow rate and the downstream pressure head are set at the constant values $Q_0 = 0.58$l/s and $H^{\text{Valve}}_{0} = 45$m, respectively. The transient regime is caused by a sudden closure of the downstream valve, initiating an upsurge pressure wave. Thereby, the boundary condition corresponding to such a maneuver may be written as:

$$Q_{x=L,t>0} = 0 \text{ and } H_{x=0,t>0} = H^{\text{Reservoir}}_{0} \tag{7}$$

For such a situation, the compound technique-based inline strategy (Figure 1(b)) consists of replacing a downstream short section of the existing steel piping system by a couple of two sub-short sections made of (HDPE-LDPE) plastic materials. However, the dual technique-based inline strategy (Figure 1(c)) consists of replacing up- and downstream sub-short sections of the existing steel pipe by other ones made of (LDPE) material. The sub-short sections lengths and diameters used in the compound or dual techniques are chosen equal to $l^{\text{compound/dual}}_{\text{sub short-section}} = 2.5$ m and $d^{\text{compound/dual}}_{\text{sub short-section}} = 53.2$ mm, respectively. Incidentally, as per relation (6), the sub-short section length and diameter used in the protected system cases based on the inline or branching conventional technique are equal to:

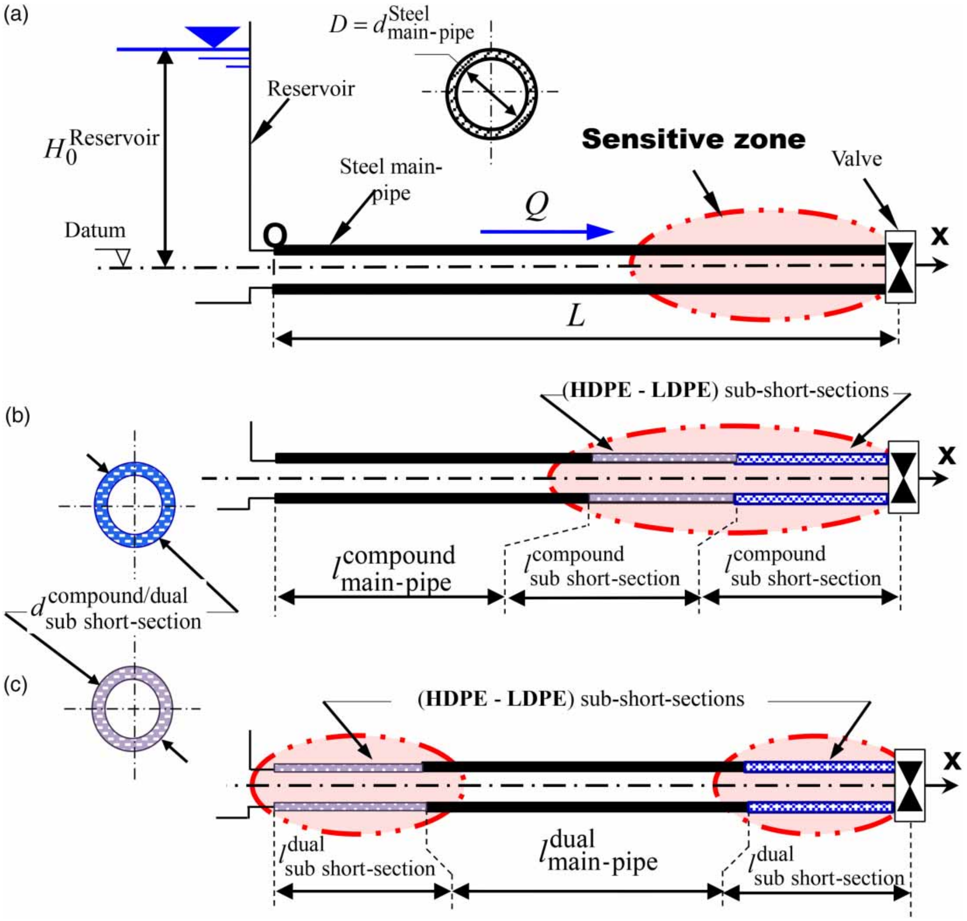

Figure 1 | Schematic setups of (a) the original system case and the protected system cases based on the (b) compound or (c) dual techniques.

$l_{\text{short-section}}^{\text{conventional}}(=2\times l_{\text{sub short-section}}^{\text{compound/dual}})=5\text{m}$ and $d_{\text{short-section}}^{\text{conventional}}$ $(=d_{\text{sub short-section}}^{\text{compound/dual}}=D)=53.2\,\text{mm}$, respectively.

Figure 2 replicates the downstream pressure head signals involved in the original system case alongside those performed by the protected system cases implementing the compound- or dual technique-based inline strategy, and the inline or branching strategies using the conventional technique. Jointly, the full characteristic set for the computed pressure head waves, associated with Figure 2, is reported in Table 1.

Based on the data shown in Figure 2 (together with Table 1), the following interpretations may be carried out for the first cycle of pressure wave oscillation.

First, Figure 2 and Table 1 show that the pressure head signal performed by the (HDPE-LDPE) setup-based protected system case exhibits attenuated trends as compared with that involved in the original system case. On this point, the attenuations of first pressure head peak involved in an (HDPE-LDPE) setup of the compound technique is $\delta H_{\text{up-surge}}^{\text{Steel}}=13.7$ m. In other words, the attenuation ratio of the first pressure head peak involved in this protected system case is about $\eta H_{\text{up-surge}}^{\text{Steel}}=66.20\,\%$.

As well, referring to Figure 2 and Table 1, it is clear that the (HDPE-LDPE) setup-based compound technique induces a spreading of pressure wave oscillation period. Specifically, the phase-shift depicted between the protected system case based on an (HDPE-LDPE) configuration of the compound technique and the original system case is equal to $\delta T_1^{\text{Steel}}=0.480$ s.

Second, Figure 2 (together with Table 1) indicates that the (HDPE-LDPE) setup-based compound technique allows more attenuation of first pressure head peak as compared to the (LDPE-LDPE) setup of the dual technique. Precisely, the attenuation of the first pressure head peak

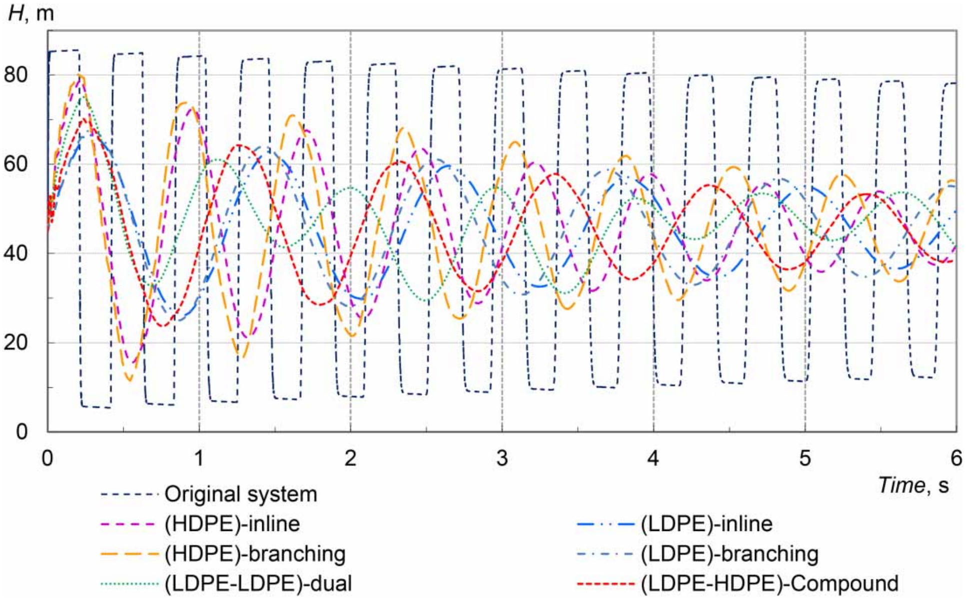

Figure 2 | Comparison of pressure head signals, at the downstream valve section, for the hydraulic system with and without implementation of the protection technique: compound, dual or conventional technique-based inline strategy; or conventional technique-based branching strategy.

involved in an (HDPE-LDPE) configuration-based compound technique, is equal to $\delta H_{\text{up-surge}}^{(\text{LDPE}-\text{LDPE})-\text{dual}} = 5.5$ m. This, in turn, implies that the (HDPE-LDPE) setup-based compound technique allows an attenuation ratio of the first pressure head peak equal to $\eta H_{\text{up-surge}}^{(\text{LDPE}-\text{LDPE})-\text{dual}} = 89.15\%$, relatively to the (LDPE-LDPE) setup-based dual technique.

On the other hand, Figure 2 shows that the (HDPE-LDPE) setup-based compound technique induces a wave oscillation period spreading comparable to an (LDPE-LDPE) configuration-based dual technique. In this regard, the phase-shift deduced between the (HDPE-LDPE) setup-based compound technique and the (LDPE-LDPE) configuration-based dual technique is equal to $\delta T_1^{(\text{LDPE}-\text{LDPE})-\text{dual}} = -0.018$ s.

Third, Figure 2 (together with Table 1) reveals that the (HDPE-LDPE) setup-based compound technique provides a more important attenuation of the first pressure head peak than the (HDPE) inline short section-based conventional technique. Particularly, the attenuation of the first pressure head peak involved in an (HDPE-LDPE) setup-based compound technique, is equal to $\delta H_{\text{up-surge}}^{(\text{HDPE})-\text{inline}} = 6.1$ m. On this point, the (HDPE-LDPE) setup-based compound technique allows an attenuation ratio of the first pressure head peak equal to $\eta H_{\text{up-surge}}^{(\text{HDPE})-\text{inline}} = 81.62\%$, relatively to the (HDPE) inline short section-based conventional technique. Contrarily, according to Figure 2 and Table 1, the (HDPE-LDPE) setup-based compound technique provides a less important

Table 1 | Characteristics of first cycle of water hammer upsurge in Figure 2

		Configurations of the controlled systems					
		Conventional inline technique		**Conventional branching technique**			
Parameters	**Original system Steel main pipe**	**(HDPE)**	**(LDPE)**	**(HDPE)**	**(LDPE)**	**Dual inline technique (LDPE-LDPE)**	**Compound inline technique (HDPE-LDPE)**
$H_{\max}$ (m)	85.6	77.9	65.3	80.1	67.6	75.1	71.9
$H_{\min}$ (m)	5.4	17.7	27.5	11.5	24.9	29.5	21.9
T (s)	0.420	0.756	1.180	0.748	1.166	0.918	0.900

attenuation of first pressure head peak as compared with the (LDPE) inline short section-based conventional technique. In particular, the attenuation of the first pressure head peak involved in (HDPE-LDPE) setup is equal to $\delta H_{\text{up-surge}}^{(\text{LDPE})-\text{inline}} = -6.6\ \text{m}$. In other words, the (HDPE-LDPE) setup-based compound technique leads to an amplification ratio of first pressure head peak equal to $\eta H_{\text{up-surge}}^{(\text{LDPE})-\text{inline}} = 132.31\%$, relatively to the (HDPE) inline short section-based conventional technique.

On the other hand, Figure 2 and Table 1 illustrate that the (HDPE-LDPE) setup-based compound technique induces a more important spreading of pressure wave oscillation period as compared to the (HDPE) inline short section-based conventional technique. In this regard, the phase-shift observed between the (HDPE-LDPE) configuration of the compound technique and the (HDPE) inline short section-based conventional technique is equal to $\delta T_1^{(\text{HDPE})-\text{inline}} = 0.144\ \text{s}$. However, Figure 2 (together with Table 1) shows that the (HDPE-LDPE) setup-based compound technique involves less important phase-shift, as compared with the conventional technique employing an (LDPE) inline short section (i.e., $\delta T_1^{(\text{LDPE})-\text{inline}} = -0.280\ \text{s}$). This signifies that the phase-shift ratio allowed by an (HDPE-LDPE) configuration of the compound technique, relatively to the (LDPE) inline short section-based conventional technique, is equal to $\eta T_1^{(\text{LDPE})-\text{inline}} = 76.27\%$.

Fourth, Figure 2 (together with Table 1) reveals that the (HDPE-LDPE) setup-based compound technique provides a more important attenuation of the first pressure head peak than an (HDPE) branched short section-based conventional technique. Specifically, the attenuation of the first pressure head peak involved in an (HDPE-LDPE) setup-based compound technique, is equal to $\delta H_{\text{up-surge}}^{(\text{HDPE})-\text{branching}} = 8.2\ \text{m}$. On this point, the (HDPE-LDPE) setup-based compound technique allows an attenuation ratio of the first pressure head peak equal to $\eta H_{\text{up-surge}}^{(\text{HDPE})-\text{branching}} = 76.55\%$, relatively to the (HDPE) branched short section-based conventional technique. Contrarily, according to Figure 2 and Table 1, the (HDPE-LDPE) setup-based compound technique provides a less important attenuation of first pressure head peak as compared with the (LDPE) branched short section-based conventional technique. In this situation, the attenuation of the first pressure head peak allowed by (HDPE-LDPE) setup is equal to $\delta H_{\text{up-surge}}^{(\text{LDPE})-\text{branching}} = -4.3\ \text{m}$. In other words, the (HDPE-LDPE) setup-based compound technique leads to an amplification ratio of the first pressure head peak equal to $\eta H_{\text{up-surge}}^{(\text{LDPE})-\text{branching}} = 118.88\%$, relatively to the (HDPE) branched short section-based conventional technique.

As well, Figure 2 illustrates that the (HDPE-LDPE) setup-based compound technique induces less important spreading of wave oscillation period as compared to the (HDPE) branched short section-based conventional technique. Specifically, the phase-shift observed between the (HDPE-LDPE) configuration-based compound technique and the (HDPE) branched short section-based conventional technique is equal to $\delta T_1^{(\text{HDPE})-\text{branching}} = 0.152\ \text{s}$. In other words, the (HDPE-LDPE) setup-based compound technique leads to a phase-shift ratio equal to $\eta T_1^{(\text{HDPE})-\text{branching}} = 120.32\%$, relatively to the (HDPE) branched short section-based conventional technique.

However, the (HDPE-LDPE) setup-based compound technique involves less phase-shift as compared with the conventional technique employing an (LDPE) branched short section: $\delta T_1^{(\text{LDPE})-\text{branching}} = -0.266\ \text{s}$. This signifies that the phase-shift ratio allowed by the compound technique based on an (LDPE-HDPE) configuration relatively to the (LDPE) configuration-based conventional technique is equal to $\eta T_1^{(\text{LDPE})-\text{branching}} = 77.19\%$.

Case 2: Downsurge-initiated water hammer event

The test case (Figure 3(a)) relates to a sloping steel piping system ($L = 100\ \text{m}$; $D = 53.2\ \text{mm}$; $e = 3.35\ \text{mm}$; $a_0^{\text{Steel}} = 1369.7\ \text{m}/s$ and $J_0^{\text{Steel}} = 0.0049\ \text{GPa}^{-1}$), connecting two pressurized tanks and equipped with a ball valve at its inlet. Initially, the upstream tank level is $z_u = 2.03\ \text{m}$, above the downstream pipe axis considered as the datum level ($z_d = 0\ \text{m}$). The steady-state regime was established for a constant flow velocity and hydraulic head values equal to $V_0 = 1.04\ \text{m/s}$ and $H_0^{T_2} = 21.4\ \text{m}$, respectively, prior to a transient event corresponding to the instantaneous and full closure of the upstream ball valve. The boundary conditions associated with such an event may be expressed as follows:

$$Q_{x=0,t\succ0} = 0 \text{ and } H_{x=L,t\succ0} = H_0^{T_2} \tag{8}$$

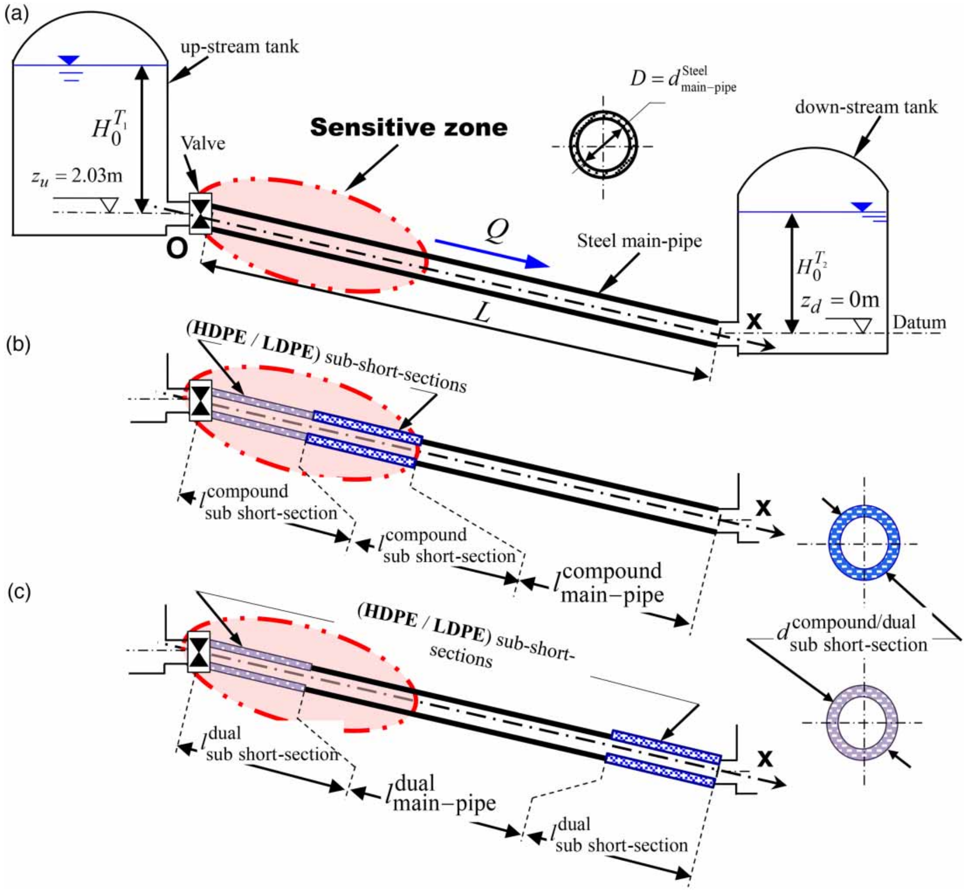

Figure 3 | Schematic setups of (a) the original system case and the protected system cases based on the (b) compound or (c) dual techniques.

In such a situation, the compound technique-based inline strategy consists of substituting an upstream short section of the main steel pipe by two plastic sub-short sections made of (LDPE-HDPE) materials (Figure 3(b)). Likewise, the dual technique-based inline strategy consists of substituting up- and downstream sub-short sections of the main steel pipe by two plastic sub-short sections made of (LDPE-LDPE) materials (Figure 3(c)).

The sub-short section length and diameter values, used in the compound or dual technique-based inline strategy, are equal to $l^{\text{compound/dual}}_{\text{sub short-section}} = 5\ \text{m}$ and $d^{\text{compound/dual}}_{\text{subshort-section}} (= D) = 53.2\ \text{mm}$, respectively. Thereupon, referring to Equation (6), the short sections' lengths and diameters used in the conventional technique-based inline or branching strategies, are: $l^{\text{conventional}}_{\text{short-section}} = 2 \times l^{\text{compound/dual}}_{\text{sub short-section}} = 10\ \text{m}$ and $d^{\text{conventional}}_{\text{short-section}} = d^{\text{compound/dual}}_{\text{subshort-section}} (= D) = 53.2\ \text{mm}$, respectively.

Figure 4 illustrates the evolution of upstream pressure head signals, involved in the original hydraulic system case, along with the corresponding signals predicted in the protected system cases using an (LDPE-HDPE) setup-based compound technique, an (LDPE-LDPE) configuration-based dual technique, an (HDPE) or (LDPE) setup-based conventional inline technique, and an (HDPE) or (LDPE) setup-based conventional branching technique. Jointly, the main features of the pressure wave curves, plotted in Figure 4, are listed in Table 2.

As can be seen from Figure 4, such a water hammer event leads to the occurrence of the unfavorable cavitation phenomenon, into the original system case. However, this phenomenon is mitigated in all protected system cases. Also, Figure 4 and Table 2 show spreading effects of pressure wave oscillation period in all protected system cases.

According to Figure 4 and Table 2, the following interpretations may be carried out for the first cycle of pressure wave oscillation.

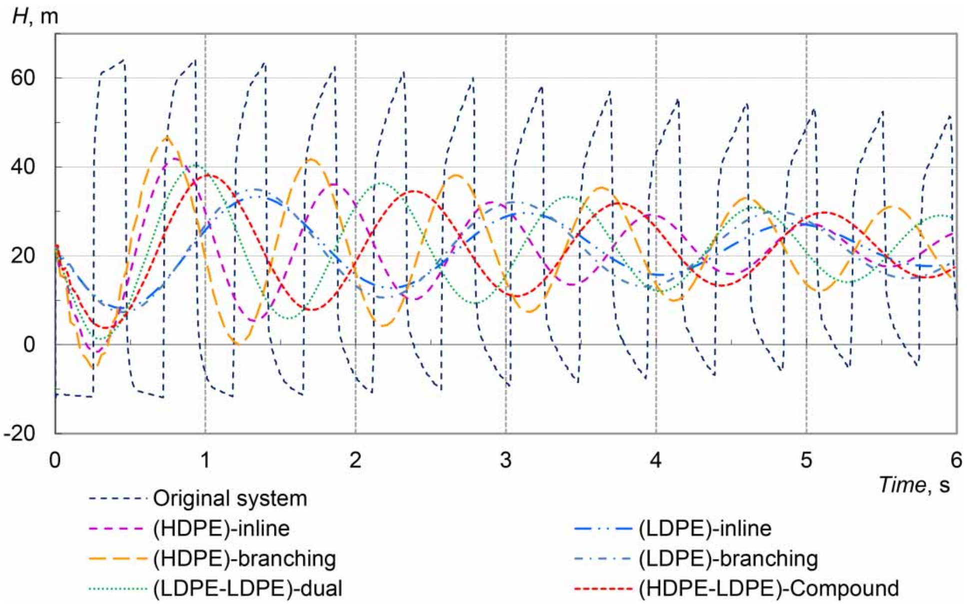

Figure 4 | Comparison of pressure head signals, at the upstream valve section, for the hydraulic system with and without implementation of the protection technique: compound, dual or conventional technique-based inline strategy; or conventional technique-based branching strategy.

First, Figure 4 reveals that the protected system case based on an (LDPE-HDPE) setup-based compound technique provides attenuated value of pressure head crest, as compared to that predicted in the original system case. Namely, the attenuation of the first pressure head crests involved in an (LDPE-HDPE) setup-based compound technique, is $\delta H^{\text{Steel}}_{\text{down-surge}} = 14.2\ \text{m}$. This, in turn, implies that the (LDPE-HDPE) configuration of the compound technique allows an attenuation ratio of the first pressure head crest equal to $\eta H^{\text{Steel}}_{\text{down-surge}} = 55.07\,\%$.

As well, it may be observed from Figure 4 (and Table 2) that the (LDPE-HDPE) setup-based compound technique induces a large spreading of pressure wave oscillation period as compared to the original system case. On this point, the phase-shift induced by an (LDPE-HDPE) compound technique is equal to $\delta T^{\text{Steel}}_{1} = 0.835\ \text{s}$.

Second, Figure 4 (and Table 2) shows that the (LDPE-HDPE) setup-based compound technique allows more attenuation of first pressure head crest than the (LDPE-LDPE) setup-based dual technique. In this case, the attenuation of the first pressure head crest involved in an (LDPE-HDPE) setup-based compound technique is $\delta H^{(\text{LDPE}-\text{LDPE})-\text{dual}}_{\text{down-surge}} = 2.3\ \text{m}$. In return, the attenuation ratio of the first pressure head crest involved in an (LDPE-HDPE) configuration case is equal to $\eta H^{(\text{LDPE}-\text{LDPE})-\text{dual}}_{\text{down-surge}} = 84.25\%$.

On the other hand, Figure 4 (and Table 2) shows that the (LDPE-HDPE) setup-based compound technique induces a more important spreading of pressure wave oscillation

Table 2 | Characteristics of first cycle of water hammer downsurge in Figure 4

		Configurations of the controlled systems					
		Conventional inline technique		**Conventional branching technique**			
Parameters	**Original system Steel main pipe**	**(HDPE)**	**(LDPE)**	**(HDPE)**	**(LDPE)**	**Dual inline technique (LDPE-LDPE)**	**Compound inline technique (LDPE-HDPE)**
$H_{\max}$ (m)	63.7	42.9	33.3	46.6	34.9	40.1	37.9
$H_{\min}$ (m)	−10.3	−3.1	8.5	−5.6	7.3	1.6	3.9
T (s)	0.535	1.120	1.800	1.020	1.790	1.235	1.370

period as compared to the (LDPE-LDPE) setup-based dual technique. Specifically, the phase-shift deduced between the two foregoing setups is $\delta T_1^{(\mathrm{LDPE-LDPE})-\mathrm{dual}} = 0.135$ s. This, in turn, implies that the phase-shift ratio between the pressure wave oscillation period induced by an (LDPE-HDPE) setup-based compound technique and an (LDPE-LDPE) configuration-based dual technique is about $\eta T_1^{(\mathrm{LDPE-LDPE})-\mathrm{dual}} = 110.931\%$.

Third, Figure 4 reveals that the (LDPE-HDPE) setup of the compound technique provides significant attenuation of the first pressure head crest as compared with the conventional one using an (HDPE) inline short section. Specifically, the attenuation of the first pressure head crest involved in an (LDPE-HDPE) sub-short section, is $\delta H_{\mathrm{down\text{-}surge}}^{(\mathrm{HDPE})-\mathrm{inline}} = 7.0$ m. This, in turn, leads to an attenuation ratio of first pressure head crest equal to $\eta H_{\mathrm{down\text{-}surge}}^{(\mathrm{HDPE})-\mathrm{inline}} = 71.59\%$. Contrarily, the (HDPE-LDPE) setup-based compound technique provides a less important attenuation of first pressure head crest, as compared to the (LDPE) inline short section-based conventional technique. In particular, Figure 4 and Table 2 indicate that the attenuation of the first pressure head crest involved in the (LDPE-HDPE) setup is $\delta H_{\mathrm{down\text{-}surge}}^{(\mathrm{LDPE})-\mathrm{inline}} = -4.5$ m. In other words, the amplification ratio of the first pressure head crest, involved in this compound technique setup, is equal to $\eta H_{\mathrm{down\text{-}surge}}^{(\mathrm{LDPE})-\mathrm{inline}} = 135.20\%$.

On the other hand, Figure 4 (and Table 2) replicates that the (LDPE-HDPE) setup-based compound technique involves more important spreading of pressure wave oscillation period than the (HDPE) inline short section-based conventional technique. Specifically, the phase-shift observed between the two foregoing techniques is equal to $\delta T_1^{(\mathrm{HDPE})-\mathrm{inline}} = -0.430$ s. In other words, the phase-shift ratio between the pressure wave oscillation induced by an (LDPE-HDPE) sub-short section-based compound technique is about $\eta T_1^{(\mathrm{HDPE})-\mathrm{inline}} = 122.321\%$.

Furthermore, Figure 4 (and Table 2) indicates that the (LDPE-HDPE) setup-based compound technique involves lower phase-shift as compared with that issued from the (LDPE) inline short section-based conventional technique. On this point, the phase-shift estimated between an (LDPE-HDPE) setup-based compound technique and an (LDPE) setup-based conventional technique is equal to $\delta T_1^{(\mathrm{LDPE})-\mathrm{inline}} = 0.250$ s. In other words, the phase-shift ratio allowed by an (LDPE-HDPE) setup-based compound technique is equal to $\eta T_1^{(\mathrm{LDPE})-\mathrm{inline}} = 74.44\%$, relatively to an (LDPE) inline short section-based conventional technique.

Fourth, Figure 4 (and Table 2) reveals that the (HDPE-LDPE) setup-based compound technique provides a more important attenuation of the first pressure head crest than the conventional technique based on an (HDPE) branched short section. Specifically, the attenuation of the first pressure head crest involved in an (HDPE-LDPE) setup-based compound technique, is equal to $\delta H_{\mathrm{down\text{-}surge}}^{(\mathrm{HDPE})-\mathrm{branching}} = 8.7$ m. On this point, the (HDPE-LDPE) setup-based compound technique allows an attenuation ratio of the first pressure head crest equal to $\eta H_{\mathrm{down\text{-}surge}}^{(\mathrm{HDPE})-\mathrm{branching}} = 65.58\%$, relatively to the (HDPE) setup-based conventional technique. Contrarily, Figure 4 illustrates that the (HDPE-LDPE) setup-based compound technique provides a less important attenuation of first pressure head peak as compared with an (LDPE) branched short section-based conventional technique. In this respect, the attenuation of the first pressure head peak involved in the (HDPE-LDPE) setup is equal to $\delta H_{\mathrm{down\text{-}surge}}^{(\mathrm{LDPE})-\mathrm{branching}} = -3.0$ m. In other words, the (HDPE-LDPE) setup-based compound technique leads to an amplification ratio of first pressure head crest, equal to $\eta H_{\mathrm{down\text{-}surge}}^{(\mathrm{LDPE})-\mathrm{branching}} = 122.42\%$, relatively to the (HDPE) branched short section-based conventional technique.

In addition, according to Figure 4 (and Table 2), the (HDPE-LDPE) setup-based compound technique induces a more important wave oscillation period spreading as compared to an (HDPE) branched short section-based conventional technique. Specifically, the phase-shift observed between the two foregoing configurations is equal to $\delta T_1^{(\mathrm{HDPE})-\mathrm{branching}} = 0.4$ s. This signifies that the phase-shift ratio allowed by an (HDPE-LDPE) configuration of the compound technique relatively to the (LDPE) configuration-based conventional technique is equal to $\eta T_1^{(\mathrm{HDPE})-\mathrm{branching}} = 134.3\%$. Interestingly, the (HDPE-LDPE) setup-based compound technique involves less phase-shifts as compared with the conventional technique employing an (LDPE) branched short section (i.e., $\delta T_1^{(\mathrm{LDPE})-\mathrm{branching}} = -0.4$ s). This signifies that the phase-shift ratio allowed by the compound technique based on an (HDPE-LDPE) configuration relatively to an (LDPE) branched short section-based conventional technique is equal to $\eta T_1^{(\mathrm{LDPE})-\mathrm{branching}} = 76.5\%$.

CONCLUSION

Overall, the findings evidenced that the utilization of plastic short section is a useful design tool for upgrading existing steel pipe-based water supply systems facing both upsurge- and downsurge-initiated water hammer events. Furthermore, results proved that the compound and dual techniques based inline strategy improved the conventional technique-based inline or branching control strategies, in terms of attenuation of pressure head and limitation of wave oscillation period spreading. Additionally, the key advantage of the compound technique-based inline control strategy over the dual one, lie in the spreading of wave oscillation period. Specifically, comparison has shown that the specific configuration of the compound technique based on (HDPE-LDPE) sub-short sections (where the former sub-short section is attached to the hydraulic parts, while the latter is attached to the main steel pipe) allows smaller wave oscillation period spreading than the specific setup of the dual technique based on an (LDPE-LDPE) sub-short section; while involving similar attenuations of pressure head peak or crest.

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