Alternative Design Strategy for Water-Hammer Control in Pressurized-Pipe Flow

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Abstract. This paper proposed a design technique to dampen water-hammer surges into an existing steel piping system based on replacing a short-section of the transient sensitive region of the main piping system by another one made of polymeric material. The flow behavior was described using a one dimensional unconventional water hammer model based on the Ramos formulation to account for pipe-wall deformation and unsteady friction losses. The numerical solver was performed using the fixed gird Method of Characteristics. The effectiveness of the proposed design technique was assessed with regard to water-hammer up-surge scenario, using a high- or low-density polyethylene (**HDPE** or **LDPE**) for the replaced short-section. Results demonstrated that the utilized technique provided a useful tool to soften severe water-hammer surges. Additionally, the pressure surge softening was slightly more important for the case of a short-section made of **LDPE** polymeric material than that using an **HDPE** polymeric material. However, it was observed that the proposed technique induced an amplification of the radial-strain magnitude and spread-out of the period of wave oscillations. It was also found that the amortization of pressure amplitude, and reciprocally the radial strain magnitude, was strongly dependent upon the short-section size and material.

Keywords: Protective device · Water-hammer control · Polymeric material **LDPE**-**HDPE**-pipe-wall material · Ramos model Fixed-grid method of characteristics

1 Introduction

Pressurized-pipe systems are subject to water-hammer surge, or flow shocks, whether induced by setting or accidental maneuvers. Incidentally, these maneuvers may trigger a series of positive and negative surges of sharp magnitude large enough to induce undesirable effects such as excessive noise, fatigue and stretch of the pipe wall and disruption of normal control.

Accordingly, water-hammer control constitutes a major concern for hydraulic researchers and designers in order to ensure a global economic efficiency and safety operations of pressurized-pipe systems. Although water-hammer surge cannot be

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avoided completely, certain design measures are commonly taken to mitigate effectively the severe impact of these waves to a desirable extent.

On the other hand, recent researches on pipe-wall materials have shown that polymeric materials, such as high- or low-density polyethylene (**HDPE** or **LDPE**), provide a significant damping of transient pressure fluctuations during high and low pressure surge loading (Pezzinga 2002; Covas et al. 2004a, b, 2005; Brinson and Brinson 2008; Triki 2016, 2017a, b, c). Thereby, the rheological behavior of viscoelastic materials brings about a great damping of the fluid pressure fluctuations, in contrast to elastic pipes where there is no delay between the pressure rise/drop and the pipe wall expansion/contraction (Covas et al. 2004a, b, 2005).

Considering the foregoing behavior of polymeric material, Massouh and Comolet (1984) examined experimentally the efficiency of adding a short rubber pipe in series to a main pipeline as an up-surge suppressor. The authors showed that the over pressure was significantly damped with gradually varied oscillations and a relatively long period. Concurrently, Triki (2016, 2017a, b, c) investigated the efficiency of the inline/branching design strategy using (**HDPE** or **LDPE**) short section. Specifically, the author (Triki 2016) used the Ramos formulation based one-dimensional water-hammer model for numerical simulation. Results addressed only pressure-head evolutions.

In order to deliver more desirable design estimates of supplement parameters such as the circumferential-stress and the radial-strain evolutions, numerical investigations are extended in this paper to illustrate the two latter parameters which are importantly embedded in the design stage of hydraulic systems.

This paper is outlined into four parts: following this introduction, the one-dimensional (**1-D**) pressurized-pipe flow model using the Ramos formulation, to describe both pipe-wall viscoelasticity and unsteady friction effects, is briefly presented. The transient flow computation is based on the Fixed Grid Method of Characteristics (**FG-MOC**), with specified time step. Thereafter, typical water-hammer up-surge scenarios are analyzed and discussed. Finally, summary and conclusions are drawn in Sect. 4.

2 Materials and Methods

One of the simplest (**1-D**) pressurized-pipe flow models, characterizing unsteady frictions and pipe-wall viscoelastic behavior, is the one proposed by Ramos et al. (2004):

$$\frac{\partial H}{\partial t} + \frac{a_0^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + g\frac{\partial H}{\partial x} + g\left(h_{f_s} + \frac{1}{gA}\left(k_{r1}\frac{\partial Q}{\partial t} + k_{r2}a_0\,Sgn(Q)\left|\frac{\partial Q}{\partial x}\right|\right)\right) = 0 \tag{2}$$

where H is the piezometric head; Q is the flow discharge; A is the cross sectional area of the pipe; g is the gravity acceleration; $a_0 = \sqrt{K/\rho/1 + \alpha(D/e)KJ_0}$ is the wave speed; x and t are the longitudinal coordinates along the pipeline axis and the time, respectively; α is a dimensionless parameter that depends on the pipe cross-section and axial constraints ($\alpha = 1$, for thin wall elastic pipes (Wylie and Streeter 1993); D is the pipe inner diameter; e is the pipe wall thickness; K is the bulk elasticity modulus of the fluid; ρ is the fluid density; J_0 is the elastic creep compliance; $k_{r1} = 0.003$ and $k_{r2} = 0.04$ are two decay coefficients (Ramos et al. 2004), affecting the phase shift and the damping of the transient pressure waves, respectively.

The quasi-steady head loss component per unit length, h_{f_s}, is computed for turbulent and laminar flow, respectively, as follows:

$$h_{f_s} = RQ|Q| \quad \text{and} \quad h_{f_s} = \frac{32v'}{gD^2A}Q \tag{3}$$

where, $R = f/2DA$ is the pipe resistance; v' is the kinematic fluid viscosity and f is the Darcy-Weisbach friction factor.

On notes that the total circumferential stress σ and the total radial strain ε may be expressed as follows (Wylie and Streeter 1993):

$$\sigma = \frac{\alpha' \Delta p D}{2e} \quad \text{and} \quad \varepsilon = \frac{\sigma}{E_0} \tag{4}$$

where: p is the pressure and $E_0 = 1/J_0$ is the Young modulus.

The numerical solution of the initial boundary value problem governed by the momentum and continuity Eqs. (1) and (2) is typically developed using the (FG-MOC) for handling multi-pipe systems with variable wave speeds. Briefly, the corresponding compatibility equations, solved by the finite difference scheme along the set of characteristic lines, yield (Ramos et al. 2004):

$$\mathbf{C}^{j^{\pm}} : \left(H^j_{i,t} - H^j_{i\pm1,t-\Delta t}\right) \pm \frac{a^j_0}{gs^j}\left(Q^j_{i,t-\Delta t} - Q^j_{i\pm1,t-\Delta t}\right) \pm a^j_0 \Delta t h_{f^j_{i\pm1,t-\Delta t}} = 0 \quad \text{along} \quad \frac{\Delta x^j}{\Delta t} = \pm\frac{a^j_0}{C^j_r} \tag{5}$$

in which, C^j_r is the Courant number used to allow the grid points to coincide with the intersection of the characteristic curves; the upper subscript j refers to the pipe number ($1 \le j \le np$) and the lower subscript i refers to the section number of the jth pipe ($1 \le i \le n^j_s$); n^j_s is the number of sections of the jth pipe and np is the number of pipes; Δt and Δx are the time and the space step increments, respectively.

For the series junction of multi-pipes, constant flow rates (i.e., no flow storage at the junction) and a common hydraulic grade-line elevation (i.e., continuous) are assumed at the junction, for each time step.

Accordingly, these assumptions yield:

$$Q^{j-1}_{x=L^{j-1},t} = Q^j_{x=0,t} \quad \text{and} \quad H^{j-1}_{x=L^{j-1},t} = H^j_{x=0,t} \tag{6}$$

where the right hand of Eq. (6) refers to the values of the hydraulic parameters just upstream of the junction, and the left hand refers to the location just downstream of the junction.

3 Application, Results and Discussion

This section aims to apply the protection technique to dampen water-hammer surges. The hydraulic system considered herein (Fig. 1), initially consists of (i.e. without implementing the protection technique) a constant head reservoir ($H_0 = 45\,\text{m}$) and a main steel pipeline equipped with a free discharge valve at its outlet. The main steel pipeline specifications are illustrated in Table 1. The initial steady state flow rate is $Q_0 = 0.58\text{l/s}$. The water-hammer surge is generated by a fast and full closure of the downstream valve with a constant pressure-head condition maintained at the upstream reservoir. The boundary conditions, associated with such a scenario, may be expressed as follows:

$$Q_{|x=L} = 0 \quad \text{and} \quad H_{|x=0} = H_{0R}\ (t \succ 0) \tag{7}$$

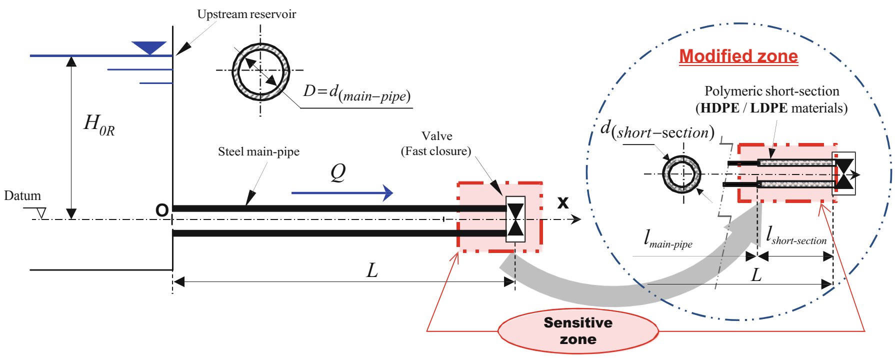

Fig. 1. Definition sketch of the hydraulic system.

Figure 1 presents a schematic layout for the implementation of the protection technique. This technique consists in replacing a downstream short-section (i.e. at the location where the surge disturbance is initiated) of the main steel piping system by another one made of a polymeric pipe-wall material, including **HDPE**- or **LDPE** material. The short-section specifications are listed in Table 1. It is worth noting that the length of the initial steel piping system (i.e. without protection) is $L = 100\,\text{m}$; however, after modification, this length is reduced to $l_{main\text{-}pipe}$ = 95 m.

One notes that the calculations of water-hammer courses were performed using an algorithm based on the **FG-MOC**, using a specified time step $\Delta t = 0.018\,\text{s}$ and Courant numbers $C_r^{main-pipe} = 0.9709$ and $C_r^{short-section} = 1$, corresponding to the steel main pipe and the polymeric short section.

Table 1. Characteristics of applied pipelines

Parameters	Steel	**HDPE**	**LDPE**
Length L [m]	100.0	5.0	5.0
Diameter D [m]	50.6	50.6	50.6
Young modulus [GPa]	210.0	1.43	0.643

Figure 2a, b and c displays the comparison between the piezometric head, the circumferential stress and the radial strains, respectively, versus time, computed at the downstream end ($x = L$) predicted from water-hammer calculations into a piping system made of a steel main-pipe (i.e. system without protection), along with the corresponding results computed for the protected system composed of series junctions of a steel main-pie and **HDPE** or **LDPE** short-section.

Figure 2a illustrates the pressure-head amortization effects of the first peak along with the spread-out of the pressure-head oscillations period, in the protected system cases. Results reveal that, for the first cycle of pressure-head oscillations, the larger overpressure is observed for the steel main-pipe case ($H_{Max.}^{steel\ pipe} = 82.719\,\text{m}$), while the corresponding value is attenuated when implementing the protection technique using HDPE and LDPE materials for the short-section ($H_{Max.}^{(steel\ +\mathbf{HDPE})\ pipe} = 76.758\,\text{m}$ and $H_{Max.}^{(steel\ +\mathbf{LDPE})\ pipe} = 69.263\,\text{m}$). In other words, the up-pressure attenuations obtained using **HDPE** and **LDPE** short-section materials are, respectively: $\Delta H = H_{Max.}^{steel\ pipe} - H_{Max.}^{(steel\ +\mathbf{HDPE})\ pipe} = 5.961\,\text{m}$ and $\Delta H = H_{Max.}^{steel\ pipe} - H_{Max.}^{(steel\ +\mathbf{LDPE})\ pipe} = 13.456\,\text{m}$. Consequently, the employed technique allows a significant amortization of the first pressure peak compared with that predicted for the same transient event initiated into the steel piping system. More precisely, this amortization is slightly more important for the case using an **LDPE** short-section (51.29%) than the one obtained using an **HDPE** short-section (23.07%).

Similarly, Fig. 2b illustrates that the employed technique also allows a significant amortization of the first circumferential-stress peak compared with the one predicted into the non-protected system. More precisely, these amortizations are slightly more important for the case using an **LDPE** short-section (i.e.: 18.31% of the first circumferential-stress peak) than those obtained using an **HDPE** short-section (i.e.: 58.28% of the first circumferential-stress peak).

Inversely, Fig. 2c shows that the damping effects of pressure-head and circumferential-stress peaks, discussed above, are accompanied with an amplification of the total radial strain peaks. More precisely, for the case using a short-section made of **HDPE**, the magnitude of the first strain peak is $\Delta\varepsilon_{up-surge}^{(steel\ +\mathbf{HDPE})\ pipe} = 2.22 \times 10^{-3}\text{m/m}$. A more important amplitude is observed for the case using an **LDPE** short-section, corresponding to: $\Delta\varepsilon_{up-surge}^{(steel\ +\mathbf{LDPE})\ pipe} = 3.16 \times 10^{-3}\,\text{m/m}$. This result may be physically explained by the viscoelastic behavior of polymeric pipe wall material which has a retarded strain, in addition to the instantaneous strain observed in elastic pipe wall material. Incidentally, the corresponding amplitude was equal to $\Delta\varepsilon_{up-surge}^{steel\ pipe} = 2.88 \times 10^{-5}\text{m/m}$, for the non-protected system case, which corresponds to the elastic radial deformation component only.

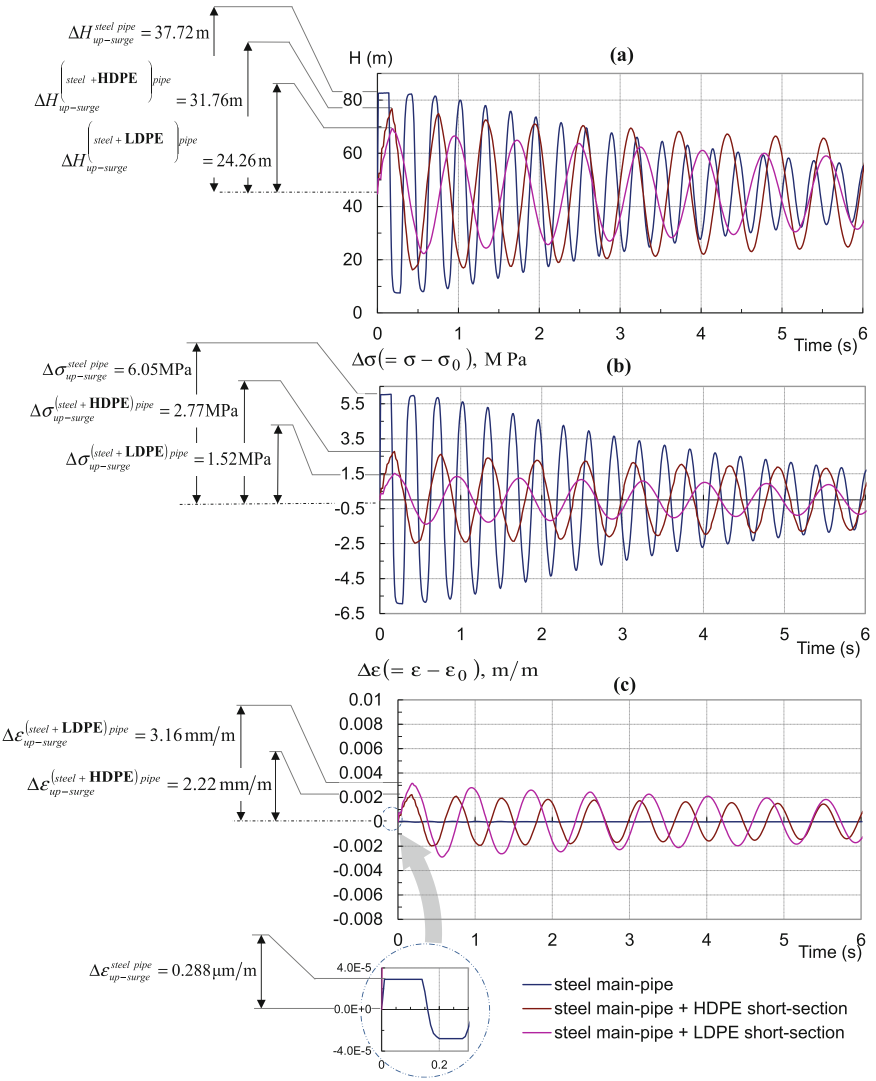

Fig. 2. Comparison of (a) piezometric heads, (b) circumferential stresses and (c) radial strains at the downstream valve section versus time for the hydraulic system with and without implementation of the protection procedure.

In addition, based on Fig. 2a, b and c, it is remarkable to observe that the periods of the first cycle of pressure-head oscillations, predicted for the protected system, are: $T_{1^{st}\ Cycle}^{(steel+\mathbf{HDPE})pipe} = 1.3\,\text{s}$ and $T_{1^{st}\ Cycle}^{(steel+\mathbf{LDPE})pipe} = 3.73\,\text{s}$ for the cases of short-sections made of **HDPE** and **LDPE** polymeric materials, respectively, while the corresponding period, for the piping system without protection (i.e. steel main pipeline), is equal to $T_{1^{st}\ Cycle}^{steel\ pipe} = 0.4\,\text{s}$. Thus, the use of polymeric short-sections induces the spread-out of the period of pressure-head oscillations. Consequently, the final subsequent steady state regime takes more time to be reached in the case of the protected system than in the case of the system without protection.

The first phase of test experiments has shown the ability of the proposed technique to soften water-hammer surge. It will be interesting to study the magnitude sensitivity of the first maximum pressure peak to the size of the replaced polymeric short-section.

So as to accurately depict this sensitivity, the maximum pressure-head peak traces at the downstream end versus time for the protected system using **HDPE** and **LDPE** polymeric materials, with the short-section length and diameter being the controlling variables, are shown in Fig. 3a and b, respectively. Specifically, the following set of diameters and lengths are performed: $d_{(short-section)} = \{0.025; 0.0506; 0.075 \text{ and } 0.1\,\text{m}\}$ and $l_{(short-section)} = \{1; 2.5; 5; 7.5 \text{ and } 10\,\text{m}\}$.

As expected, these graphs reveal that the variation of the short-section size affects the magnitude of the maximum peak of transient pressure oscillations. In other words, as the replaced short-section volume increases, the associated damping effect of the maximum pressure head increases. More precisely, Fig. 3a clearly illustrates that, for the length

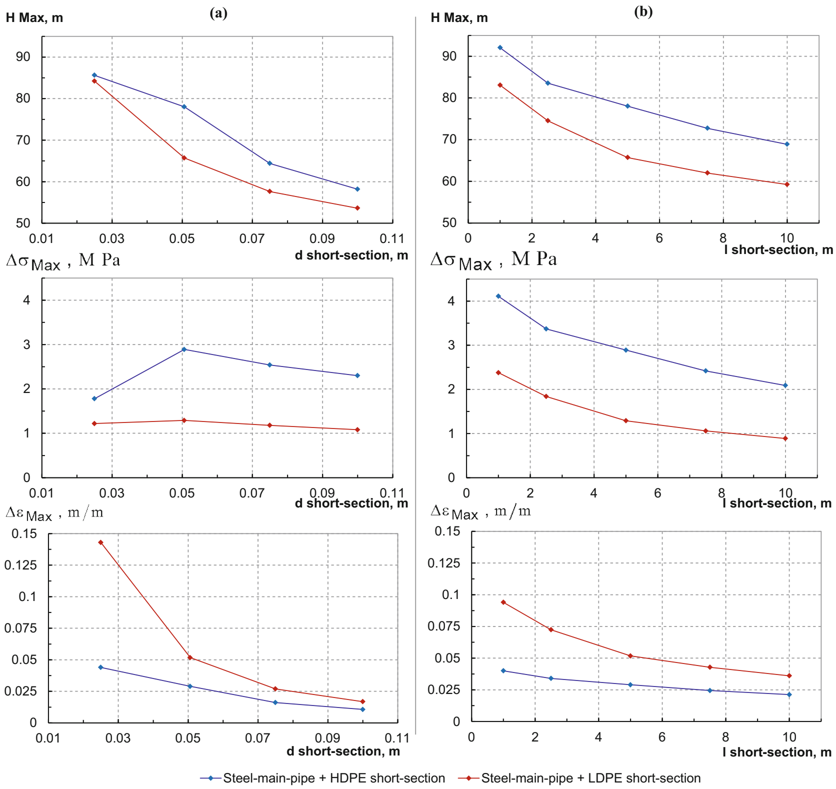

Fig. 3. Variation of maximum piezometric heads, stresses and strains, at the downstream valve section, for the protected system with a polymeric (**HDPE/LDPE**) short-section: variation depending on the short-section (a) diameter and (b) length.

values $l_{(short-\sec tion)} = 1$ m and 2 m, the maximum peak decreases significantly. However, for the length values beyond $l_{(short-\sec tion)} \geq 5$ m, the variation of the maximum transient pressure peak is slightly affected. Similarly, analysis of Fig. 3b indicates that as the diameter of the polymeric short section increases from $d_{(short-\sec tion)} = 0.025$ m to 0.0506 m, the maximum pressure peak is significantly damped. However, this amortization is not pronounced for the diameter values beyond $d_{(short-\sec tion)} \geq 0.075$ m. Thereby, $l_{(short-\sec tion)} = 5$ m and $d_{(short-\sec tion)} = 0.075$ m may be considered as the optimal values of the polymeric short section diameter and length.

4 Conclusion

In summary, the present study has illustrated that the proposed protection technique is effective in softening severe water-hammer surge. It is remarkable to observe that the employed technique provides a large damping of the first pressure peak associated with a transient initiating event. However, the foregoing behavior is accompanied with the amplification of radial strain peaks and the spread-out of the period of wave oscillations. In addition, the pressure damping (and reciprocally, the radial-strain amplification) is observed to be more pronounced when using an **LDPE** polymeric material for the replaced short sections than an **HDPE** material. It is also shown that other factors contributing to the damping rate of pressure head and the radial-strain amplification depend upon the short-section size (i.e. length and diameter). On the other hand, examination of the sensitivity of the pressure peak magnitude, with the short-section length and diameter being the controlling variables, verifies that significant volumes of the short section provide important pressure surge damping and radial-strain amplification. However, this correlation is not significant beyond optimum diameter and length values.

Overall, such a technique may greatly enhance the reliability and improve the cost-effectiveness of pressurized-pipe utilities, while safeguarding operators. It is estimated that these findings are of practical importance in the design measure side for the mitigation of severe water-hammer surges.

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