Uncertainty Analysis of Transient Flow Modeling and Transient-Based Leak Detection in Elastic Water Pipeline Systems

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Abstract: In the transient flow modeling and analysis of practical water pipeline systems, discrepancies commonly exist between numerical simulation results and experimental measurement data. Such discrepancies are usually accounted for the inaccuracy and inadequacy of the used mathematical models and/or the lack of understanding of the hydrodynamic physics for transient pipe flows in the literature. However, the variability or uncertainty of the parameters for such numerical model inputs may also attribute to these discrepancies, especially in complex pipeline systems. This paper investigates the effects of different system uncertainties on the transient flow modeling and analysis such as pipe system design and leak detection. Different factors of pipe and fluid properties as well as system operations and complexities are considered for the uncertainty analysis. The one-dimensional (1D) water hammer model and the Monte-Carlo simulation (MCS) method are used in this investigation. The analysis results in this study demonstrate that the variability of the transient flow modeling can be easily affected by the uncertainty factors of wave speed and system complexities, while the transient-based leak detection is more sensitive to the uncertainty factors of wave speed and data measurement than the factors of valve operation and initial hydraulic condition.

Keywords: Water pipelines · Uncertainty analysis · Transient flow modeling · Leak detection · Monte-Carlo simulation (MCS) · Sensitivity

1 Introduction

Pipe fluid transients are fast moving pressure waves that are commonly triggered by rapid changes in pipe flows. In engineering practice, transient flows exert decisive influences on practical aspects of engineering design, operation and management of pipeline systems

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(Wylie et al. 1993). In recent years, transient waves are also used to detect leakages, blockages and other defects in pipes (Colombo et al. 2009). Therefore, many mathematical models have been developed for prediction and evaluation of pipe fluid transients in order to better understand, design, and protect pipeline systems. The classical one-dimensional (1D) water hammer model is widely used for the analysis for its efficient computation and simple coding, by coupling with multiple dimensional principles and physics.

In practical applications, obvious discrepancies commonly exist between the numerical prediction results and field measurement data, which have been observed frequently in previous studies (e.g., McInnis and Karney 1995; Stephens 2008; Ebacher et al. 2011). The common treatment method for reducing these discrepancies in the literature is to improve the transient modeling techniques and theory such as numerical computation scheme and turbulence (unsteady friction) modeling (Wylie et al. 1993), which has been widely explored in the past decades and has made significant contributions in this field. However, these applications showed that the variability or uncertainty of the model inputs for numerical simulations could also attribute to such discrepancies, in addition to the inadequacy of current numerical models and methods, especially in practical complex systems. Usually, the parameters in the 1D water hammer models, such as wave speed, pipe diameter, friction, and operation conditions, are considered as deterministic inputs, which are actually encountered with many uncertainties due to natural variations (e.g., corrosion, sediments, biofilm in pipeline) and/or human behaviors (e.g., valve operation and demand variation) in real-life pipe systems (Tung et al. 2006; Duan et al. 2010; Edwards and Collins 2014). Understanding these uncertainty features is important and essential to the engineering applications of transient pipe flows as well as the theoretical development of transient flow models and analysis methods. While many previous studies have focused on the uncertainty analysis of water pipe networks under steady state conditions (e.g., Pasha and Lansey 2011; Seifollahi-Aghmiuni et al. 2013; Haghighi and Asl 2014; Marques et al. 2014), only very few studies so far have focused on the uncertainty analysis in the field of pipe fluid transients.

With regard to transient flow modeling, Wiggert (1999) studied the uncertainty features of system responses caused by the variations of wave speed, pipe friction, and valve motions in a single pipeline system. It was found in his study that the resulted uncertainty of the system responses (pressure and discharge) propagates (increasing or decreasing) with time for different inputs during a typical water hammer event. However, this study and analysis was conducted based on a first-order Taylor series expansion of finite-difference representation of 1D water hammer equations, where the nonlinear and high-order (order ≥ 2) correlations between the responses and input parameters were assumed to be negligible. Thereafter, Rougier and Goldstein (2001) proposed a Bayesian updating based approach to generalize water hammer equations by incorporating uncertainties in coefficients of pipe properties, boundary conditions, and model solution. But their proposed uncertainty analysis framework is applicable only when historical flow measurement data are available in the system. A recent study by the Author in Duan et al. (2010) has investigated the probabilistic modeling for the design of the transient pipeline system and associated protection devices (e.g., air-chamber and surge-tank) for the water supply pipeline system. In their study, a robust tool, Monte-Carlo simulation (MCS), has been adopted for the investigation. Their results indicated that the deterministic analysis may underestimate the threat of cavitation due to minimum (negative) pressure while, at the same time, could overestimate the potential of pipe rupture from the maximum (positive) pressure. Furthermore, it was also concluded in their study that probabilistic analysis of transients could provide a good alternative with a great deal of information for prudent design of newly water supply pipeline systems and risk/reliability evaluation of existing pipeline systems.

With regard to leak detection in water pipelines, pipe leakages have become one of the main sources of water and energy losses worldwide and many transient-based leak detection methods were developed for the use in water piping systems due to the advantages in terms of speed, ability to work online and large operational range (Colombo et al. 2009; Duan et al. 2011; Meniconi et al. 2011; Haghighi and Ramos 2012). But so far these developed transient-based leak detection methods have not yet been applied to practical and complex pipe systems. One of the main reasons is due to the incapability of such methods in dealing with different complexities and uncertainties encountered in real-life applications. These uncertainty sources affecting the leak detection may include: parameter estimation (Ramos et al. 2009; Duan et al. 2010; Kumar et al. 2010), demand and device operation (Baños et al. 2011), and data measurement errors (Rougier and Goldstein 2001). Consequently, a systematic investigation of the influences of these uncertainty sources on the transient flow modeling as well as transient-based leak detection is necessary and important for practical application purpose.

Based on the previous study of Duan et al. (2010), this paper investigates the impacts of different uncertainty factors in water pipeline systems on the transient flow modeling and analysis (leak detection), with the aim to establish a framework for uncertainty analysis of transient pipe systems and thus to provide fundamental basis for urban water resources management. The MCS method is adopted for probabilistic modeling and the frequency domain method from Duan et al. (2011) is used for inspecting the leak detection problems in this paper. For illustration, the situations of elastic pipelines and transients without cavitation are considered in this numerical study.

2 Models and Methods

2.1 Transient flow modeling

The 1D water hammer model is adopted in this study for the investigation and the governing equations are given as below (Wylie, et al. 1993),

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

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{\pi D}{\rho}\tau_w = 0\,, \tag{2}$$

where H and Q are pressure head and discharge; ρ is fluid density; g is gravitational acceleration; a is wave speed; D and A are the diameter and cross-sectional area of pipeline; x and t are spatial and temporal coordinates; τ_w is wall shear stress. In this study, the wave speed (a) in Eq. (1) is considered by the combined effect of various pipe and fluid properties including the elasticity of fluid and pipe-wall material, fluid density, pipe constraint, pipe-wall thickness, and pipe size (Wylie et al. 1993; Duan et al. 2010). Meanwhile, wall shear stress τ_w in the momentum Eq. (2) is represented by the sum of quasi-steady and unsteady friction components, which are calculated by the classic Darcy-Weisbach formula (Wylie et al. 1993) and the Vardy's weighting-function based model (Vardy and Brown 1995), respectively. The method of characteristics (MOC) is adopted in this study to solve the above

1D water hammer equations (1) and (2) (Wylie et al. 1993).

2.2 Transient-based leak detection

The frequency domain transient-based leak detection method developed in Duan et al. (2011) is adopted for the illustration in this study. The leak-induced damping pattern of frequency domain peak responses has a general form for both the single pipeline and multiple-pipe in series systems as (Duan et al. 2011),

$$h^* = \frac{S_{L0}}{C_{M0}}\left[1 + \cos\left(2m\left(1 - x_L^*\right)\right)\right], \tag{3}$$

where h^* is converted transient pressure head in the frequency domain; S_{L0} is resistance coefficient of leak orifice under steady state; x_L^* is dimensionless leak location; and C_{M0} is coefficient relating to the pipe connection complexity and its detailed expression refers to Duan et al. (2011). In the single and series pipeline systems, the expressions of S_{L0} and x_L^* are defined respectively as,

$$S_{L0} = \frac{Q_{L0}}{4H_{L0}} \quad \text{and} \quad x_L^* = \frac{x_L}{L_0}, \tag{4}$$

where Q_{L0} and H_{L0} are discharge and head at leak location under initial steady (pre-transient) state; m is number of frequency peaks; x_L is distance of leak location from upstream end; and L_0 is total length of pipeline under investigation. The influence of different uncertainty factors to the leak detection accuracy based on Eq. (3) is explored later in this paper.

2.3 MCS-based uncertainty analysis

In transient flow modeling and utilization analysis, it is impossible to obtain the exact solution of the system responses due to the complexity of models, e.g., Eq. (1) through Eq. (3). Therefore, in this study, the rigorous tool of MCS is used to provide numerical estimations for the uncertainty analysis of such transient pipe systems (Duan et al. 2010). The flowchart and general procedures of the MCS applied into uncertainty analysis of transient pipe flow systems is shown in Fig. 1. Based on prior convergence test for different pipe systems considered in this study, the maximum number of the MCS runs is set at 5000 for the analysis (Tung et al. 2006, Duan et al. 2010). The uncertainty of inputs and parameters is partially based on the analysis results of previous studies (e.g., Wiggert 1999; Duan et al. 2010) and are presented in the following sections.

Figure 1 is inserted here

Fig. 1 Flowchart of MCS for transient analysis

3 Numerical Experiments

3.1 Description of testing pipe systems

Two hypothetical pipeline systems with different connection complexities in Fig. 2 are used for investigation, where Fig. 2(a) is for a typical single-pipeline system and Fig. 2(b) for a 3-series-pipe system with a variation of pipe diameters along the pipeline. In these two systems, the pipeline is bounded by two constant-head reservoirs/tanks (i.e., H_0 and H_s), and the pipe flowrate is adjusted by the downstream valve. Meanwhile, all the minor head losses in each pipe system are lumped to the local valve loss at the downstream end. The settings of other hydraulic conditions and system parameters for these two systems are depicted as in the figure. Initially the systems are under steady state with flow rate Q_s is 0.2 m^3/s (i.e., the downstream valve is fully open). Transients are then generated by the fast closure of the downstream valve. The transient pressure head is collected at the just upstream of the valve for analysis.

In this study, two different situations of leak-free (intact) and leaking pipelines as depicted in the figure are considered in each system for the purposes of transient flow modeling and analysis (leak detection). For the leak detection in these two systems, the pipe leakage information are evaluated by the dimensionless location (x_L^*) and resistance coefficient (S_{L0}) given in Eq. (3) and Eq. (4).

Figure 2 is inserted here

Fig. 2 Pipeline systems for the illustration: (a) single-pipe system; (b) series-pipe system

3.2 Uncertainty of inputs and parameters

Duan et al. (2010) has investigated the uncertainties of different parameters in water supply pipeline systems, including pipe properties (e.g., Young's modulus of elasticity, diameter, and thickness), internal fluid mixture properties (e.g., density, bulk modulus of elasticity, and air content), and system characteristic (e.g., constraint factor). Based on the results obtained in previous studies (Wiggert 1999; Duan et al. 2010), the uncertainty factors considered in this study include :

(1) Wave speed (a): (μ_a, σ_a) with lognormal distribution as obtained in Duan et al. (2010) where μ_a and σ_a are mean and standard deviation of wave speed, and μ_a = 480 m/s and σ_a = 153 m/s;

(2) Valve operation time (τ_v): [0, $0.1L_0/a_0$] with upper triangular distribution;

(3) Initial Reynolds number ($\mathbf{Re}_0$): [$0.9\mu_{Re}$, $1.1\mu_{Re}$] with uniform distribution, where μ_{Re} is expected value of initial steady state Reynolds number;

(4) Measured/extracted frequency-domain peak amplitude (h_ω): [$0.9\mu_h$, $1.1\mu_h$] with uniform distribution, where μ_h is expected value of resonant peak amplitude.

It is important to mention that the values of μ_{Re} and μ_h are calculated from the deterministic modeling based on the parameters given in the systems in Fig. 2. Moreover, in this study, the first three factors (1), (2) and (3) are used to investigate the uncertainty of transient modeling for system design, while all these four factors are applied to inspect the uncertainty of transient-based leak detection based on Eq. (3).

4 Results and Discussions

Based on the analysis procedure given in Fig. 1, the results are obtained for the transient flow modeling responses and leak detection with statistical quantities of mean and standard deviation. Under deterministic conditions, the transients are caused by the sudden closure of the end valve in the above two pipe systems. The results of deterministic and probabilistic calculations are compared and discussed for the transient flow modeling and transient-based leak detection respectively in the following study.

4.1 Transient modeling for system design

Transient flow modeling, based on the envelope and evolution of transient responses, is generally used to design pipe strength for new systems or to evaluate the performance and risk of failure in existing systems. Under the deterministic conditions, the results of pressure head at the downstream valve for above two systems are plotted in Fig. 3(a) and (b) respectively. In Fig. 3, the vertical coordinate (ΔH^*) depicts the transient pressure head (i.e., $\Delta H_t = H_t - H_0$), normalized by the *Joukowsky* head (i.e., $\Delta H_0 = a\Delta Q/gA$ at the valve), while axial coordinate (t^*) represents the dimensionless time in terms of theoretical wave period of the corresponding system (i.e., $T_w = 4\Sigma L_i/a_i$). Meanwhile, the envelopes of transient pressure head along the pipeline are shown in Figs. 4(a) and (b) for the two systems respectively, which indicates the possible maximum positive and negative pressures in the system. The axial coordinate in Fig. 4 refers to the dimensionless distance from upstream reservoir along the pipeline (i.e., $x^* = x/L_0$). Figures 3 and 4 demonstrate that under the deterministic condition (without any uncertainty), the maximum envelope pressures (positive and negative) in the 3-series-pipe system are much larger than those in the single pipe system. Therefore, the transient design is more crucial in the systems with higher pipe connection complexities. As compared to the single pipeline system, the pressure envelopes of the 3-series-pipe system vary strongly along the pipeline, which are actually decreasing with the distance from the transient source location (i.e., the downstream valve in this study). Therefore, the pipe connection complexities (junctions) are found to have potential influences on the uncertainty results (amplitudes and propagation) which are further studied and discussed in the following section.

Under the uncertainty conditions, the transient responses can be calculated by MCS procedure given in Fig. 1. Taking the wave speed factor (1) for example, the results of transient pressure head at valve are obtained and plotted in Figs. 5(a) and (b) for the two pipeline systems shown in Fig. 2 respectively, where the variability range of the transient response is represented by the mean value (μ_H) plus/minus the standard deviation (σ_H) based on the statistical results of MCS outputs.

<u>Figure 3 is inserted here</u>

Fig. 3 Transient pressure head at the valve by deterministic modeling for: (a) single-pipe system in Fig. 2(a); (b) series-pipe system in Fig. 2(b)

Figure 4 is inserted here

Fig. 4 Transient envelope along the pipeline by deterministic modeling for: (a) single-pipe system in Fig. 2(a); (b) series-pipe system in Fig. 2(b)

To fairly evaluate the uncertainty propagation in different pipe systems, the variability of the obtained transient responses is defined by the dimensionless sensitivity coefficient, β, as (Tung et al. 2006),

$$\beta_{X_j} = \frac{\partial H}{\partial X_j}\frac{\mu_{X_j}}{\Delta H_0} \approx \frac{\sigma_H / \Delta H_0}{\sigma_{X_j} / \mu_{X_j}}, \tag{5}$$

where the subscript X_j indicates the uncertainty factor causing the variability of the response, including a, τ_v and $\mathbf{Re}_0$ in this section. Based on Eq. (5), the calculated results are plotted in Figs. 6(a) and (b) (i.e., the black solid lines) which reveal that the variability of transient response in the single pipe system is relatively larger than that in the 3-series pipe system, under the same conditions of transients and wave speed uncertainty.

Figure 5 is inserted here

Fig. 5 Transient responses of pressure head at valve end with uncertainty of wave speed for: (a) single-pipe system in Fig. 2(a); (b) series-pipe system in Fig. 2(b)

Similarly, the uncertainty propagations of the transient pressure head at valve due to other uncertainty factors (i.e., factors (2) and (3)) are calculated and shown in Figs. 6(a) and (b) to make a comparison for the two testing pipeline systems respectively. The comparative results indicate that in both pipeline systems the uncertainty of wave speed (a) is the most critical factor to the variability of the transient responses, then followed by the valve operation (τ_v) and initial hydraulic condition ($\mathbf{Re}_0$). Moreover, the results in Figs. 6(a) and (b) demonstrate that for each uncertainty factor, the induced variability of transient responses in simple pipe systems is relatively larger than that in complex systems. Therefore, the pipe connection complexities may have great influences to the uncertainty magnitudes and propagation in complex pipe systems. This is mainly because the various wave reflections occurring at pipe junctions during the transient flow process may cause the serious wave trapping and superposition along the pipeline, such that the uncertainty propagation has also been limited greatly in the system. The detailed influences of different pipe connection complexities are systematically investigated and summarized in this study based on the sensitivity analysis.

Figure 6 is inserted here

Fig. 6 Comparison of the influences of different uncertainty factors for: (a) single-pipe system in Fig. 2(a); (b) series-pipe system in Fig. 2(b)

4.2 Transient-based leak detection

To apply Eq. (3) for the transient-based leak detection, the transient responses obtained from numerical modeling or data measurement have to be converted into the frequency domain by using Fourier transform (Kreyszig 1993; Duan et al. 2011). For illustration, the converted results for the two pipeline systems in Fig. 2 with single leakage case in the pipeline are shown in Figs. 7(a) and (b) respectively, where the axial coordinate is the dimensionless frequency (ω^*) normalized by the fundamental frequency of the system (ω_{fd} = $1/T_w$). For comparison, the results of intact (leak-free) pipelines are also plotted in the same figure. The results of both pipe systems show clearly the damping of different transient peaks due to the leakage in the system which is also called as leak-induced damping “pattern” in the literature. The transient peaks in the frequency domain are then extracted and used to inversely solving Eq. (3) to obtain the leakage information (leak size and location) (see Duan et al. 2011).

Figure 7 is inserted here

Fig. 7 Transient frequency responses for: (a) single-pipe system in Fig. 2(a); (b) series-pipe system in Fig. 2(b)

As shown in Table 1, four leaking pipeline cases with different leak information are examined in this study for illustration, with case no. 1 used for single pipe system of Fig. 2(a), and cases no. 2 ~ no. 4 for the system of Fig. 2(b). The dimensionless leakage Q_{L0}^* is defined by the leaking flowrate relative to initial discharge in pipeline under steady state, i.e., Q_{L0}/Q_0.

Since the parameters S_{L0} and Q_{L0}^* in Table 1 are equivalent to describe the size of leakage according to Eq. (3), only Q_{L0}^* is used in the following analysis for clarity.

Table 1 is inserted here

Table 1 Settings for leaking pipe systems

Based on the MCS procedure given in Fig. 1, the leak detection results for different uncertainty conditions are obtained and listed in Table 2. The mean value (μ) and standard deviation (σ) of predicted leak information are presented and used for evaluating the accuracy and variability of the detection results. Overall results from Table 2 indicate that under the specified uncertainty conditions: (i) the accuracy of leak detection in the series-pipe system is lower than that in the single pipeline; and (ii) the uncertainty factors of wave speed (a) and data measurement (h_ω) have greater influences on the leak detection accuracy, than the other two factors (τ_v and $\mathbf{Re}_0$).

Table 2 is inserted here

Table 2 Uncertainty of leak detection results (μ = mean, σ = standard deviation)

To quantitatively analyze the statistical results in Table 2, the mean values of leak detection (location and size) by the MCS procedure provided in Fig. 1 are evaluated by the relative error, γ_p, defined by,

$$\gamma_p(\%) = \left|\frac{\mu_p - R_p}{R_p}\right| \times 100, \tag{6}$$

where μ is the mean value by MCS; R is the "real" value in Table 1; and subscript "p" refers to the leak parameters for prediction, including x_L^* and Q_{L0}^*. Moreover, the coefficient of variation (COV) is used to evaluate the variability range of each leak information prediction, and mathematically defined by (Tung et al. 2006),

$$\delta = \frac{\sigma}{\mu}. \tag{7}$$

Figure 8 is inserted here

Fig. 8 (a) relative error of the mean leak location prediction; (b) relative error of the mean leak size prediction; (c) COV of leak location prediction; and (d) COV of leak size prediction

The calculated results by Eq. (6) and Eq. (7) are plotted in Fig. 8, which further confirm the former findings with regard to the influences of system connection complexity and different uncertainty factors on the detection accuracy. The results of Fig. 8 also demonstrate that: (1) the influence of these system uncertainties on the leak size detection is larger than that on the leak location detection (see Figs. 8a & b); and (2) the variability of detection results for leak size is larger than that for leak location (see Figs. 8c & d). Consequently, it is expected that the detection of potential leak size is more difficult (less accurate) than that of leak location by using the transient-based leak detection method, which is consistent with many former observations in the literature (e.g., Colombo et al. 2009).

5 Sensitivity Analysis for Transient-Based Leak Detection

To study the sensitivity of the used leak detection method to each uncertainty factor considered in this study, it is assumed that the leak detection error is dependent on the uncertainty of each factor as well as the system complexity as,

$$\gamma(\%) = \sum_{X_j} C_{X_j} \delta_{X_j}^{S_{X_j}} + C_c(\phi_c - 1)^{S_c}, \tag{8}$$

where C and S are constant coefficients to be determined, representing the sensitivity coefficient and exponential index, respectively; δ is the COV of uncertainty factors; subscript "*c*" denotes the parameter relating to system complexity; and ϕ_c is the index for describing the system complexity. For simplicity in this study, ϕ_c is defined as the number of pipe sections. For example, ϕ_c = 1 and 3 refer to the pipeline systems as in Figs. 2(a) and (b) respectively. Moreover, for simplicity, the effects of different uncertainty factors on the variability of transient responses are assumed to be independent during the transient-based leak detection process.

Based on the procedure given in Fig. 1, extensive numerical tests have been conducted to analyze the relationship between the leak detection error (variability of detection results) and the uncertainties of different factors, which covers wide ranges of pipe scales (L_0: 100 ~ 2000 m; D_0: 0.1 ~ 1.0 m), system complexities (ϕ_c: 1 ~ 10), and system operations (τ_v: 0 ~ $4L_0/a_0$; $\mathbf{Re}_0$: 1000 ~ 100000). The obtained data are statistically analyzed with the help of an improved genetic algorithm (GA) based optimization for calibrating constant coefficients C and S in Eq. (8) (Duan et al. 2011). As a result, the error expressions for leak location and size are obtained as,

$$\gamma_{x_L^*}(\%) = 1.754\delta_a^{0.437} - 0.004\delta_{\tau v}^{0.010} + 0.001\delta_{\mathbf{Re}0}^{0.007} + 8.422\delta_{h\omega}^{0.453} + 0.141(\phi_c - 1)^{0.032}, \tag{9}$$

$$\gamma_{Q_{L0}^*}(\%) = 9.765\delta_a^{0.311} - 0.018\delta_{\tau v}^{0.011} - 0.017\delta_{\mathbf{Re}0}^{0.185} + 5.639\delta_{h\omega}^{0.203} + 0.009(\phi_c - 1)^{0.010}. \tag{10}$$

The results in Eq. (9) and Eq. (10) clearly indicate the dependence of the variability of leak detection results on each uncertainty factor. It is also found that the sensitivity of leak detection using transients is very significant to the uncertainty factors of wave speed and data measurement, followed by the system complexity, valve operation and initial flow condition. The results and findings of the sensitivity analysis may have significant implications to the practical applications of the transient modeling and analysis, including (but not limited to):

(1) more cautions need to be paid for the data measurement and pipe parameter calibrations such as wave speed;

(2) it is more accurate to apply current transient-based leak detection method to simple pipe systems with less influence of system complexity; and

(3) where uncertainties are usually inevitable, it is acceptable to present the leak detection results with a certain range of errors for practical applications in pipe systems.

It is also important to note that the sensitivity coefficients of Eq. (9) and Eq. (10) are obtained from the numerical tests under specified conditions in this study, and more systematical investigations are required to generalize the results and conclusion in the future work.

6 Conclusions and Recommendations

This paper investigates the influence of different uncertainty factors to the transient flow modeling and transient-based leak detection. Two different pipe systems with different pipe complexities and four common types of uncertainty factors (wave speed, valve operation, initial Reynolds number and data measurement) are applied to examine the uncertainty characteristics and propagation in transient flow modeling and analysis.

The obtained results in this study show that these uncertainty factors can produce a large range of variations in the results of transient flow modeling as well as transient-based leak detection, which may have been attributed wrongly to the transient model errors in the literature. Furthermore, the preliminary investigation of sensitivity analysis for the transient-based leak detection has been performed through extensive numerical applications in this study, and the analysis results imply that the transient-based leak detection is more sensitive to the uncertainty factors of wave speed and data measurement than the factors of valve operation and initial Reynolds number.

Finally, it is worthy of noting that only the relatively simple situations of pipe system configurations (single and three-series elastic pipelines) and system operations (valve operations) are investigated in this study. To generalize the results and findings of this study, more practical and complex situations, such as visco-elastic pipelines, pipe network configuration, cavitation process, and pump station operations, need to be investigated further in the future work.

Acknowledgements

This research was supported by the research grants of the Hong Kong Polytechnic University (HKPU) under projects 1-ZVCD, G-UC73 and G-YBC9.

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