State-of-the-art review on the transient flow modeling and utilization for urban water supply system (UWSS) management

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ABSTRACT

In the context of smart city development and rapid urbanization worldwide, urban water supply system (UWSS) has been of vital importance to this process. This paper presents a comprehensive review on the transient flow research for UWSS management. This review consists of two aspects as follows. The first aspect is about the development and progress of current transient theory, including transient flow models, unsteady friction and turbulence models, and numerical simulation methods. The other aspect is about the utilization and application of transient-based methods for effective UWSS diagnosis and management, including leakage, discrete and extended partial blockages, unknown branch, and other defects in water pipelines. A total of 228 publications have been reviewed and analyzed in this paper. In addition to the state-of-the-art progress and achievement of the research on transients, the advances and recommendations of future work in this field are also discussed for the development and management of next-generation smart UWSS in the paper.

Key words | smart city, smart water, transient-based defect detection (TBDD), transient modelling and analysis, urban water supply system (UWSS)

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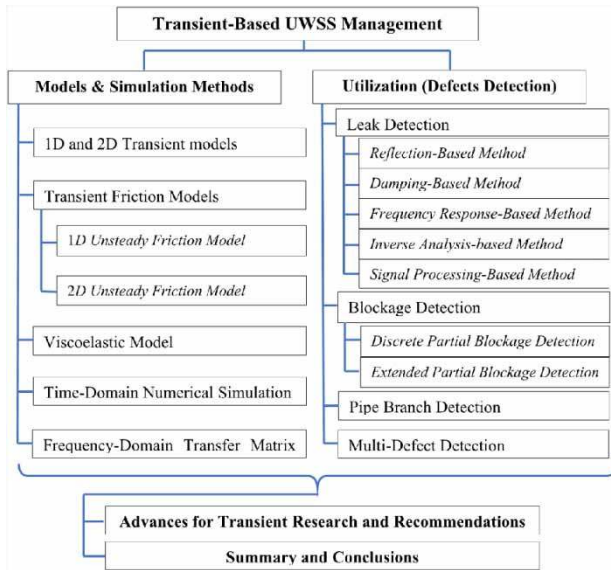China

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HIGHLIGHTS

- The development and progress of current transient theory and modelling methods have been reviewed.
- The transient-based utilization methods for different pipe defects detection have been summarized.
- The achievement and implications of transient research for UWSS management have been discussed.

GRAPHICAL ABSTRACT

NOTATION

List of main symbols used in the paper

a	wave speed;
a_c, C_B, k_1, C_m, C_c, C_m, s_k, s_e, C_{e1}, C_{e2}, f_1, f_2, f_m, f_w, R_y, R_t, R_*, y_*, y	coefficients in turbulence models;
A	πr^2 the cross-sectional area of the pipe;
A_L	leak area size;
$\mathbf{b_u}$, $\mathbf{b_v}$ $\mathbf{B}$, $\mathbf{B_1}$, $\mathbf{C}$, $\mathbf{C_1}$, $\mathbf{S}$, $\mathbf{J}$, $\mathbf{W}$, $\mathbf{R}$, $\mathbf{L}$ and $\mathbf{K}$	vectors and matrices in 2D model;
C	pipe constraint coefficient;
C_L, C_d	leak and orifice coefficients;
D	pipe diameter;
e	pipe-wall thickness;
E_{kv}	modulus of elasticity in K-V model;
f	the Darcy–Weisbach friction factor of pipeline;
$F(\cdot)$	the frequency response function (FRF) of the system;
g	gravitational acceleration;
$\hat{h}$	inverted FRF magnitude;
H	piezometric head;
H_{L0}, Z_L	original head and elevation at leak location;
ΔH_{B0}	steady state head loss across the partial blockage;
i	imaginary unit or counting number;
$I(\cdot)$	impulse response function (IRF);
I_B	partial blockage impedance;
$J(\cdot)$	creep compliance;
$J_{B1}(\cdot)$	the Bessel function;
$J_{kv} = 1/E_{kv}$	creep compliance of the k-element;
K_L	the leakage impendence factor;
l	the mixing length in turbulence model;
L	pipe section length;
m	peak number;
n	harmonic mode number;
np	leaking pipe number;

N	total number of K-V elements;	α_s	the potential leak size in the system;
Nr	the total grid number in radial direction in 2D model;	d	unsteady boundary layer thickness;
P	pressure;		
q, h	discharge (Q) and pressure head (H) in the frequency domain;	ε_A and ε_L	normalized quantities of blocked area and length in the pipeline;
Q_L	leak discharge;	e_r	total retarded strain of the viscoelastic pipe;
Q_{B0}	steady state flow across the partial blockage;	v	transverse velocity;
r	radial distance from pipe center;	v_k	kinematic viscosity of the fluid;
		v_t	turbulent eddy viscosity
		$v_T = v_t + v_k$	total viscosity;
R	radius of pipe;	v_R	radial velocity at pipe-wall due to deformation;
R_e	Reynolds number;		
R_{nL}	the leak-induced damping rate for the nth mode;	ξ_s	relative change of the characteristic impedance by the partial blockage;
R_{fs}, R_{fu}, R_f	steady, unsteady and total friction damping factors, respectively;	ρ	fluid density;
		σ	normal stress related to pressure head;
R_w	wave reflection coefficient;		
t	time;	$\sigma_x, \sigma_r, \sigma_\theta$	normal stress in longitudinal, transverse and angular directions, respectively;
t'	a dummy time variable;		
T_w, T_d	timescales of axial wave propagation and radial turbulent diffusion;	η	the weighting coefficient;
		η_{kv}	viscosity of the kv-element;
u	longitudinal velocity;	θ, β	coefficients;
$u^*, v^*, H^*, t^*, r^*, x^*, t^*, r^*$	dimensionless variables;	κ, ε	turbulent kinetic energy and dissipation rate, respectively;
$U, V, H_J, \tau_0, \rho_0, L, L/a, \delta$	scaling orders of variables u, v, H, t, ρ, x, t, r;	λ	wave propagation coefficient;
U_T	initial friction velocity;	μ	propagation operator;
$W(\cdot)$	weighting function in unsteady shear stress;	τ	shear stress;
		$\tau_{kv} = \eta_{kv}/E_{kv}$	retardation time of the kv-element;
x	spatial coordinate along the pipeline;		
x_L, x_L^*	dimensional and dimensionless leak location;	τ_t	turbulent component of shear stress;
		τ_l	laminar component of shear stress;
Y	the characteristic impedance of pipeline;		
		τ_s, τ_{ws}	quasi-steady part of shear stress and wall shear stress;
Z	fitness of objective function;		
α_k^*	roots of the equation of $J_0(\alpha_k^*) = 0$;	τ_u, τ_{wu}	unsteady part of shear stress and wall shear stress;
α, β	coefficients;	τ_w	wall shear stress;

ϕ, φ	the variables to be solved;
$\bar{\chi}$	density-weighted-averaging quantities;
χ'	density-weighted-averaging pulsation quantities;
ω	frequency of wave signal;
$\Delta\omega^*$	normalized resonant frequency shift;
ω_{rfb}	resonant frequencies of the blocked pipe system;
ω_{rf0}	fundamental frequency of intact pipeline system.

List of main acronyms used in this paper

1D	one-dimensional;
2D	two-dimensional;
ANN	artificial neural networks;
CCA	cross-correlation analysis;
CPU	central processing unit;
CUSUM	cumulative sum;
EMD	empirical mode decomposition;
FD	finite difference;
FRF	frequency response function;
FRT model	five-region turbulence model;
GA	genetic algorithm;
GCV	generalized cross validation;
GF	Gaussian function;
HDPE	high-density polyethylene;
HT	Hilbert transform;
IMAB models	instantaneous material acceleration-based models;
IRF	impulse response function;
ITAM	inverse transient analysis-based method;
IWSA	International Water Supply Association;
K-V model	Kelvin–Voigt model;
LM	Levenberg–Marquardt;
LSD	least squares deconvolution;
LSMF	least squares and match-filter;
MFP	matched-field processing;
ML	maximum likelihood;
MOC	method of characteristics;

NLP	non-linear programming;
ODE	ordinary differential equation;
PE	polyethylene;
PPR	polypropylene;
PVC	polyvinyl chloride;
QSA models	quasi-steady algebraic models;
RANS	Reynolds-averaged method;
SA	simulated annealing;
SPM	signal processing-based method;
TBDD	transient-based defect detection;
TDM	transient damping-based method;
TFRM	transient frequency response-based method;
TLB	two-layer turbulence;
TMA	transfer matrix analysis;
TRM	transient reflection-based method;
UWSS	urban water supply system;
WFB	weighting function-based.

INTRODUCTION

Water supply is a basic need for society and its security and efficiency are of paramount importance to human health and economic development. At present, the urban water supply system (UWSS) is the lifeline of over four billion people globally, the facilitator of urban economic activities, and the pillar of modern urban civilization. However, a substantial portion of these vital systems are decades old and are plagued with deficiencies and inefficiencies (Figure 1). For instance, pipelines in UWSS usually encounter many different problems that may affect the effectiveness of the system function and operation, such as leakage, partial blockage, ill-junction, corrosion, biofilm, deformation, cavitation, air-pocket, detachment, and so on, which are termed as pipe anomalies in this paper.

The formation and existence of pipe anomalies may result in serious problems, including (but not limited to) the reduction of flow capacity, increase of energy loss and deterioration of water quality. As a result, it has been estimated that the water loss attains to over 30%, on average, in the UWSSs around the world, with typical cases shown in Figure 2 (Lai *et al.* 2017; Samir *et al.* 2017; AL-Washali *et al.* 2019; Liemberger & Wyatt 2019). Moreover, the cost
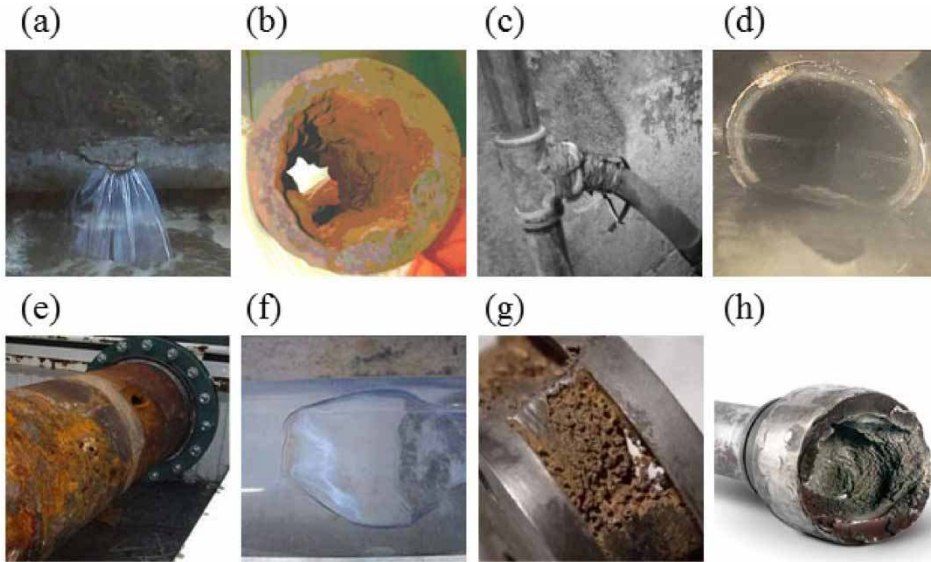
Figure 1 | Different types of pipe deficiencies in UWSS: (a) leakage; (b) partial blockage; (c) ill-junction; (d) deformation; (e) corrosion; (f) air-pocket; (g) cavitation; (h) detachment.
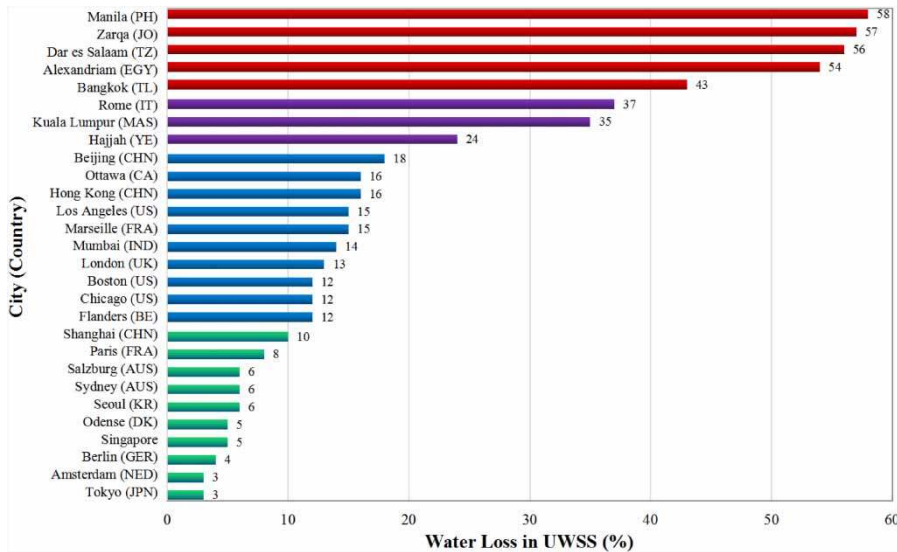

Figure 2 | Water loss situation of typical UWSSs in the world.

of energy required for pumping and supplying water in public systems is also increased significantly due to the extra water volume and energy loss from leakages and partial blockages as leakages in the pipeline cause a decrease in water pressure head to consumers and partial blockages can increase the flow velocity and head loss (Colombo & Karney 2002). From this point of view, it is urgent to develop more advanced technologies and innovative methodologies to effectively manage and diagnose the UWSS, so as to minimize the resultant problems and wastage.

Based on various theoretical development and practical application experiences in the literature, hydraulic models and models have been found to be one of the reliable and cost-effective ways to address the current adverse situations

in UWSS. To this end, this paper aims to conduct a comprehensive review of the hydraulic models for describing the highly unsteady flows (i.e., transient) that are commonly used for the effective design and management of UWSS, as well as the innovative transient-based technologies that have been widely developed in recent years for UWSS diagnosis and management. For clarity, the structure of this paper is shown in Figure 3. The paper content starts with the introduction and illustration of the importance of transients in UWSS, followed by the two aspects of this review (modeling and utilization). Thereafter, the advances and limitations of current transient models and methods are discussed with a perspective of smart UWSS development. Finally, the key contents and findings as well as recommendations on future work are summarized in the conclusion.

IMPORTANCE OF TRANSIENT PHENOMENA AND INFORMATION IN UWSS

The transient state of flows is variously termed waterhammer, fast transients, hydraulic transients, fluid transients, or pressure surges, in the literature (Wylie *et al.* 1993; Chaudhry 2014). In engineering practice across a multitude of fluid systems and applications, transient flows exert decisive influences on practical aspects of engineering design and operation of pipeline systems. As a result, transient waves are formed during the transient flow states in UWSS. Transient waves are fast moving elastic shocks that travel at relatively high velocities in pipeline systems (e.g., about 1,000 m/s in metallic pipes and around 400 m/s in polymeric pipes). They are generally triggered by planned or accidental events in pipe fluid systems that result in rapid changes in the pipe flow. Transient events may be caused by operations of valves, starting and stopping of pumps, variations in the supply or demand of the system fluid, and many other situations. These sudden changes in system flow require the imposition of large forces to accelerate or decelerate the fluid, and consequently are capable of inducing severe or even catastrophic pressures in the pipeline. For example, a waterhammer accident caused a hydro disaster in Russia's biggest hydroelectric plant in 2009 (RT 2009).

Hydraulic transients affect the structural integrity of pipelines, and this accounts for their importance in the minds and practice of design engineers. However, because they can move rapidly throughout a system, and their waveforms are modified by their propagation and reflection interactions with the pipe and its component devices, they can also be used as a potentially inexpensive and diverse source of information in integrity management applications. Transient pressure monitoring and analysis appears to hold considerable promise for estimating the state or condition of the pipeline system as it changes over time. Recently developed techniques for leak detection in water pipeline systems are utilizing the information associated with the transient damping and reflections (Colombo *et al.* 2009; Ayati *et al.* 2019).

In addition to the traditional water loss identification technology – leak listening that is still widely used nowadays, other commercially available technologies used for UWSS diagnosis mainly include two types from their implementation ways in UWSS: (i) intrusive methods, e.g., CCTV camera, gas tracer, infrared thermography, Smart Ball and robot (El-Zahab & Zayed 2019); and (ii) non-intrusive methods, e.g., moisture sensor, ground penetrating radar, acoustic correlator, and noise logger (Lee 2005). Despite the successful applications of these methods in various UWSSs, these methods are also found to be either intrusive and time-consuming (e.g., the type (i) methods above) or short ranged and expensive (e.g., the type (ii)
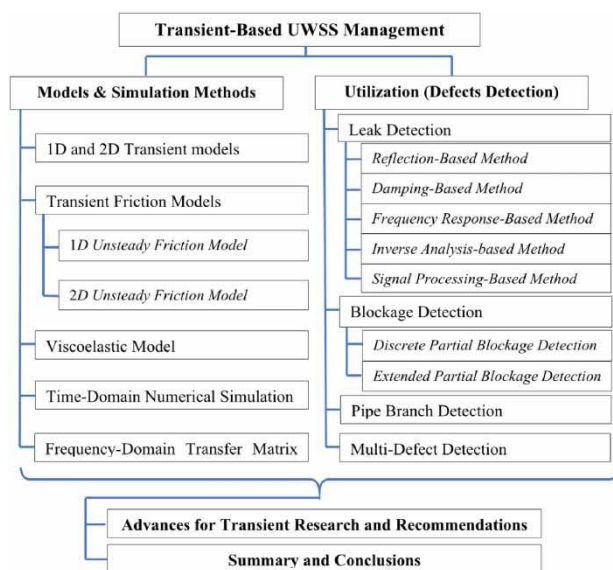

Figure 3 │ Structure of the review content.

methods above) (Gupta & Kulat 2018; Ali & Choi 2019). Moreover, the critical situation in current UWSSs (over 30% water loss in the world) demonstrates clearly the inadequacy and inefficiency of using these methods only (Stephens 2008; Puust *et al.* 2010).

Utilization of transient data for leak detection could have great practical significance since pipe leakage is a common, costly, and serious water conservation and health issue worldwide. Despite the implementation of a comprehensive pipe replacement scheme with a price tag of more than US$3.0 billion during 2000–2015 in Hong Kong (Burn *et al.* 1999), the water loss (leakage) in its UWSS still remained at about 16% in 2016, which costs over US$1.0 billion/year (source water price and treatment expenses). Moreover, the leakage situation has presented a bounce back trend in the UWSS after the pipeline replacement according to the data information in recent years. This indicates that, from a long-term perspective, it is necessary to develop and apply a more sustainable way for solving the critical leakage situation in UWSS. Since points of leakage also represent potential locations for contaminant intrusion, identification and control of leak locations are doubly important. Consequently, an improved understanding of transient flows in pipes is important to advancing the practical utilization of transients as a source of information and, at the same time, minimizing their damaging impacts on the physical infrastructure (Wylie *et al.* 1993; Ghidaoui *et al.* 2005; Chaudhry 2014).

TRANSIENT MODELS AND SIMULATION METHODS

In the field of transients or waterhammer, substantial efforts have been made by various researchers and engineers to develop transient theories and models for better design, analysis, and management of UWSS (Ghidaoui *et al.* 2005). The one-dimensional (1D) models are widely investigated and commonly used for the transient system design and analysis for their advantages of efficient computation and easy implementation in practice (e.g., Wylie *et al.* 1993; Duan *et al.* 2010a, 2010b; Chaudhry 2014) while, recently, two-dimensional (2D) or quasi-2D models that allow inclusion of different types of turbulence model have also been explored and applied for modeling transient pipe

flows (e.g., Vardy & Hwang 1991; Silva-Araya & Chaudhry 1997; Pezzinga 1999; Zhao & Ghidaoui 2006; Duan *et al.* 2009; Korbar *et al.* 2014). To replicate the transient pressure attenuation due to friction damping under transient state, many types of unsteady friction (or turbulence) models in 1D and 2D forms have been developed and discussed in the transient/waterhammer literature in the past decades (e.g., Ghidaoui 2004; Ghidaoui *et al.* 2005; Lee *et al.* 2013a; Meniconi *et al.* 2014; Vardy *et al.* 2015). These developed models and simulation schemes have been widely verified and validated through various experimental data from both laboratory and field tests. Furthermore, to extend the applicability and improve the accuracy of current transient models and methods, more complex factors in practical UWSS have been gradually investigated and included in the transient models by many researchers in this field. For example, the plastic pipe-wall deformation effect has been successfully incorporated in 1D and 2D transient models using analogous viscoelastic components, such as Kelvin–Voigt (K-V) model (e.g., Franke 1983; Güney 1983; Pezzinga 1999; Covas *et al.* 2005a; Duan *et al.* 2010c).

For the purpose of a review, the development progress and achievement of the transient models and simulation methods commonly used for the UWSS are summarized as follows.

1D and 2D transient models

In pressurized water supply pipelines, the axisymmetry assumption is usually made for investigating transient pipe flows (Figure 4), since the velocity component (momentum
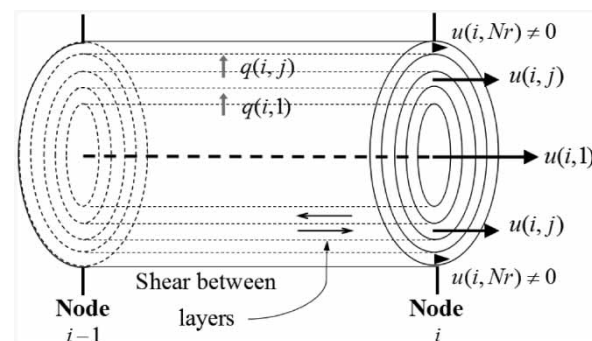

Figure 4 │ Sketch of axisymmetric flows in a pipe section (i = axial node number; j = radial node number; Nr = number of radial nodes; q = unit radial flow; u = axial velocity).

flux) in azimuthal direction of the pipe cross-sectional area is relatively small (Pezzinga 1999). Therefore, in this study, the derivation of transient model starts with the 2D Navier–Stokes equations in cylindrical coordinates for compressible pipe flows (Newtonian flow) as follows (Potter & Wiggert 1997):

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{1}{r}\frac{\partial (\rho rv)}{\partial r} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{1}{\rho}\frac{\partial \sigma_x}{\partial x} - \frac{1}{\rho r}\frac{\partial (r\tau)}{\partial r} \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial r} = -\frac{1}{\rho}\frac{\partial P}{\partial r} - \frac{1}{\rho}\frac{\partial \tau}{\partial x} - \frac{1}{\rho r}\frac{\partial (r\sigma_r)}{\partial r} + \frac{\sigma_\theta}{\rho r} \tag{3}$$

where P = pressure; ρ = fluid density; σ_x, σ_r, σ_θ = normal stress excluding the pressure stress in longitudinal, transverse, and angular directions, respectively; x = spatial coordinate along the pipeline; r = radial distance from pipe center; t = time; g = gravitational acceleration; u = longitudinal velocity; v = transverse velocity; and τ = shear stress.

For simplicity, the external normal stress forces (σ_x, σ_r, σ_θ), except the pressure force, are excluded in the following study regarding water supply pipeline problems (e.g., Pezzinga 1999; Ghidaoui *et al.* 2005). Meanwhile, the wave speed during transient pipe flows can be defined as (Wylie *et al.* 1993; Chaudhry 2014):

$$a = \sqrt{\frac{d\rho}{dP} + \frac{\rho}{A}\frac{dA}{dP}} \tag{4}$$

By considering the relations of $A = \pi r^2$ and $P = \rho gH$ in the pipeline, Equations (1)–(3) can be re-written as:

$$\frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x} + \frac{a^2}{g}\frac{\partial u}{\partial x} + \frac{a^2}{g}\frac{1}{r}\frac{\partial (rv)}{\partial r} = 0 \tag{5}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r}\right) = -\rho g\frac{\partial H}{\partial x} - \frac{1}{r}\frac{\partial (r\tau_l)}{\partial r} \tag{6}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial r}\right) = -\rho g\frac{\partial H}{\partial r} - \frac{\partial \tau_l}{\partial x} \tag{7}$$

To efficiently solve momentum equations under turbulent condition by using the Reynolds-averaged method

(RANS), the density-weighted-averaging (Favre averaging) and the ensemble-averaging are considered, respectively, as (Zhang 2002):

$$\chi = \bar{\chi} + \chi' \text{ and } \bar{\chi} = \frac{\langle \rho\chi \rangle}{\langle \rho \rangle} \tag{8}$$

in which $\chi = H, \rho, \tau_l, u, v$ represents the variable whose quantity is to be solved; $\bar{\chi}$ = the density-weighted-averaging quantities; χ' = density-weighted-averaging pulsation quantities; and $\langle \rangle$ = the ensemble-averaging quantity. Therefore, for different variables in waterhammer flows:

$$\langle \phi \rangle = \bar{\phi}; \langle \phi' \rangle = 0; \langle \rho\varphi \rangle = \langle \rho\bar{\varphi} \rangle = \bar{\varphi}\langle \rho \rangle; \langle \rho\varphi' \rangle = 0 \tag{9}$$

in which $\phi = u, v, H, \rho, \tau_l$; and $\varphi = u, v, H$. By taking the ensemble-averaging for Equations (6) and (7), and applying the relations in Equations (8) and (9), the following results are obtained:

$$\langle \rho \rangle\left(\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial r}\right) + \frac{1}{r}\frac{\partial (r\langle \rho u'v' \rangle)}{\partial r}$$
$$= \left\langle -\rho g\frac{\partial H}{\partial x} - \frac{1}{r}\frac{\partial (r\tau_l)}{\partial r}\right\rangle \tag{10}$$

$$\langle \rho \rangle\left(\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial r}\right) + \frac{\partial \langle \rho u'v' \rangle}{\partial x} = \left\langle -\rho g\frac{\partial H}{\partial r} - \frac{\partial \tau_l}{\partial x}\right\rangle \tag{11}$$

where τ_l is laminar component of shear stress. By incorporating Boussinesq assumption, and after rearranging terms, the results become:

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial r} = -g\frac{\partial \langle H \rangle}{\partial x} - \frac{1}{\langle \rho \rangle}\frac{1}{r}\frac{\partial (r\langle \tau \rangle)}{\partial r} \tag{12}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial r} = -g\frac{\partial \langle H \rangle}{\partial r} - \frac{1}{\langle \rho \rangle}\frac{\partial \langle \tau \rangle}{\partial x} \tag{13}$$

in which $\tau = \tau_l + \tau_t$ is total shear stress; and τ_t is turbulent component of shear stress.

Considering the following scales of the quantities in typical transient pipe flows (Duan *et al.* 2012a):

$$u = u^*U; v = v^*V; H = H^*H_J; \rho = \rho^*\rho_0;$$
$$\tau = \tau^*\tau_0; x = x^*L; t = t^*(L/a); r = r^*\delta \tag{14}$$

where $U, V, H_J, \tau_0, \rho_0, L, L/a, \delta$ = scaling orders of variables $u, v, H, \tau, \rho, x, t, r$, with δ = unsteady boundary layer thickness; and $u^*, v^*, H^*, \tau^*, \rho^*, x^*, t^*, r^*$ = dimensionless variables. By substituting Equation (14) into Equations (5), (12), and (13), it gives:

$$\frac{\partial H^*}{\partial t^*} + \frac{U}{a} u^* \frac{\partial H^*}{\partial x^*} + \frac{\partial u^*}{\partial x^*} + \frac{VL}{U\delta} \frac{1}{r^*} \frac{\partial(r^* v^*)}{\partial r^*} = 0 \tag{15}$$

$$\begin{aligned}
&\frac{\partial u^*}{\partial t^*} + \frac{U}{a} u^* \frac{\partial u^*}{\partial x^*} + \frac{VL}{a\delta} v^* \frac{\partial u^*}{\partial r^*} \\
&= -\frac{\partial H^*}{\partial x^*} - \frac{L\tau_0}{\rho_0 U a \delta} \frac{1}{\rho^* r^*} \frac{\partial(r^* \tau^*)}{\partial r^*}
\end{aligned} \tag{16}$$

$$\begin{aligned}
&\frac{\delta V}{LU} \frac{\partial v^*}{\partial t^*} + \frac{\delta V}{La} u^* \frac{\partial v^*}{\partial x^*} + \frac{VV}{aU} v^* \frac{\partial v^*}{\partial r^*} \\
&= -\frac{\partial \langle H^* \rangle}{\partial r^*} - \frac{\delta \tau_0}{\rho_0 U a L} \frac{1}{\rho^*} \frac{\partial \langle \tau^* \rangle}{\partial x^*}
\end{aligned} \tag{17}$$

Since $U/a \ll 1$ in typical water supply pipeline systems, the second term in both Equations (15) and (16) can be neglected. Note that in the transient pipe flow, the mass flux fluctuation in axial direction has to be balanced by that in radial direction and the mass storage of fluid compressibility, such that:

Axial mass influx = Radial mass outflux

$$+ \text{Mass storage due to fluid compressibility}$$

that is,

$$\frac{U}{L} \geq \frac{V}{\delta} \text{ or } \frac{VL}{U\delta} \leq 1 \tag{18}$$

Therefore, the fourth term in Equation (15) may be important in the transient pipe flows. Furthermore, it can be obtained in Equation (16):

$$\frac{VL}{a\delta} = \frac{VL}{U\delta} \frac{U}{a} < <1 \tag{19}$$

which indicates the third term in Equation (16) can also be negligible. For the shear stress in momentum equations, considering $\tau_0 \sim k_d \rho \, D \frac{\partial u}{\partial t}$ yields (Ghidaoui *et al.* 2005):

$$\frac{L\tau_0}{\rho U a \delta} \sim k_d.$$

Previous experimental results in the literature have shown that the coefficient k_d value varies with different transient flows and waterhammer problems under investigation and has a wide range of 0.01–0.62 (Daily *et al.* 1955; Shuy & Apelt 1983). This indicates that the turbulent shear stress in the axial momentum Equation (16) might be important to the transient pipe flow events. However, in radial momentum Equation (17), it has:

$$\frac{\delta \tau_0}{\rho_0 U a L} = \frac{L\tau_0}{\rho_0 U a \delta} \frac{\delta^2}{L^2} \ll 1 \tag{20}$$

Moreover, since $\delta \ll L$ and $V \ll U \ll a$ in pipe flows (Vardy & Hwang 1991), one has:

$$\frac{\delta V}{LU} \ll 1; \quad \frac{\delta V}{La} \ll 1; \quad \frac{VV}{aU} \ll 1$$

Therefore, the terms of inertia, convection, and shear stress in the radial momentum Equation (17) can be negligible during the transient/waterhammer process. As a result, the governing equations, Equations (15)–(17), can be simplified as:

$$\frac{\partial H^*}{\partial t^*} + \frac{Ua}{Hg} \frac{\partial u^*}{\partial x^*} + \frac{VL}{U\delta} \frac{1}{r^*} \frac{\partial(r^* v^*)}{\partial r^*} = 0 \tag{21}$$

$$\frac{\partial u^*}{\partial t^*} = -\frac{gH}{Ua} \frac{\partial H^*}{\partial x^*} - \frac{L\tau_0}{\rho U a \delta} \frac{1}{\rho^* r^*} \frac{\partial(r^* \tau^*)}{\partial r^*} \tag{22}$$

$$0 = -\frac{\partial \langle H^* \rangle}{\partial r^*} \tag{23}$$

Returning to the original equation forms of Equations (1)–(3) provides:

$$\frac{\partial H}{\partial t} + \frac{a^2}{g} \frac{\partial u}{\partial x} = -\frac{a^2}{g} \frac{1}{r} \frac{\partial(rv)}{\partial r} \tag{24}$$

$$\frac{\partial u}{\partial t} + g \frac{\partial H}{\partial x} = -\frac{1}{\rho r} \frac{\partial(r\tau)}{\partial r} \tag{25}$$

$$\frac{\partial H}{\partial r} = 0 \tag{26}$$

These actually are the commonly used quasi-2D transient flow models in the literature (e.g., Vardy & Hwang

1991; Pezzinga 1999; Zhao & Ghidaoui 2006; Duan *et al.* 2010d).

Furthermore, integrating Equations (24)–(26) throughout the cross-sectional area of pipeline, and considering the deformation of pipe-wall, provides the 1D form of transient flow model as follows:

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial U}{\partial x} + \frac{2a^2}{gR}v_R = 0 \qquad (27)$$

$$\frac{\partial U}{\partial t} + g\frac{\partial H}{\partial x} + \frac{\tau_w \pi D}{\rho A} = 0 \qquad (28)$$

where H = piezometric head; U = cross-sectional average velocity; A = pipe cross-sectional area; D = pipe diameter; τ_w = wall shear stress; v_R = radial velocity at pipe-wall due to deformation. For the third term in Equation (27), the relationship between radial velocity and pipe radial expansion is (Güney 1983; Covas *et al.* 2005b; Duan *et al.* 2010d):

$$v_R(x, t) = \frac{1}{2}\frac{\partial D}{\partial t} \text{ and } \frac{1}{D}\frac{\partial D}{\partial t} = \frac{\partial \varepsilon}{\partial t} \qquad (29)$$

where ε = viscoelastic retarded strain of pipe-wall, and it equals zero for elastic pipes:

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial U}{\partial x} + \frac{2a^2}{g}\frac{\partial \varepsilon}{\partial t} = 0 \qquad (30)$$

This 1D form of transient flow model in Equations (28) and (30) has been widely used in the study of transient flows for both viscoelastic and elastic pipelines due to the convenience of numerical implementation and the efficiency of the solution process (Wylie *et al.* 1993; Ghidaoui *et al.* 2005; Chaudhry 2014).

Transient friction models

The expression of shear stress in the momentum Equations (25) or (28) is needed to close the transient models (1D or 2D). In the literature, a 1D quasi-steady wall shear stress model represented by the Darcy–Weisbach formula is commonly used in 1D models for its explicit expression and efficient calculation (Wylie *et al.* 1993; Chaudhry 2014):

$$\tau_w(t) = \frac{\rho f(t)|U(t)|U(t)}{8} \qquad (31)$$

where f is the Darcy–Weisbach friction factor of pipeline.

However, when the transient flow is generated in the system, the pressure wave will distort the velocity profile and even create an inverse flow near the pipe wall, which is significantly different from steady flow. Therefore, the energy dissipation caused by shear stress is different and the results from experimental tests show that the quasi-steady friction model cannot capture the total friction damping because of the unsteadiness of transient flows. Therefore, the shear stress of transient flows along the radial direction (r) is artificially divided into two components in that one represents the quasi-steady part (τ_s) and the other the unsteady part (τ_u), as (Ghidaoui *et al.* 2005):

$$\tau(r) = \tau_s(r) + \tau_u(r) \qquad (32)$$

Many types of unsteady friction model have been proposed to account for the unsteady shear stress during transient flows. For example, the discrepancy between the results of pressure head traces with and without steady/unsteady friction models can be clearly found in Figure 5. The results indicate that an accurate friction model can greatly improve the accuracy of the numerical prediction with reference to the observed data. Moreover, many previous studies have already shown that the friction or turbulence behavior had a great influence on the water quality problems in pipe
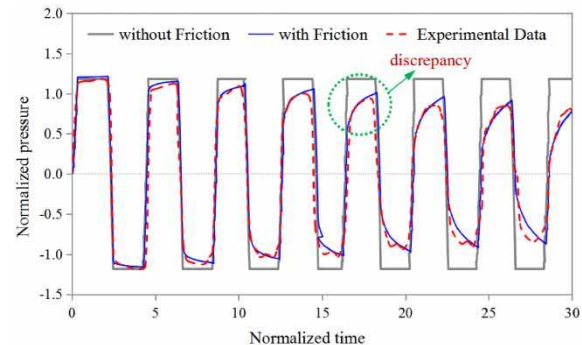

Figure 5 | Pressure head traces by numerical model with and without transient friction effect and experimental data (Bergant & Simpson 1994).

systems (Taylor 1953; Fernandes & Karney 2004; Naser & Karney 2008), which supports the argument for the necessity of the friction/turbulence models.

1D unsteady friction model

According to Equation (32), the 1D wall shear stress can be divided into two components as:

$$\tau_w = \tau_{ws} + \tau_{wu} \tag{33}$$

in which τ_{ws} and τ_{wu} are, respectively, quasi-steady and unsteady components of wall shear stress. In the waterhammer literature, the quasi-steady shear stress is usually represented by the Darcy–Weisbach friction (Wylie *et al.* 1993; Chaudhry 2014), while many other unsteady friction models have been proposed to simulate the unsteady wall shear stress component to account for the discrepancy between the instantaneous wall shear stress (τ_w) and quasi-steady component (τ_{ws}). From the previous studies, the existing 1D unsteady friction models can be summarized and classified as the following:

1. Instantaneous local acceleration-based (ILAB) formulas (e.g., Daily *et al.* 1955; Carstens & Roller 1959; Shuy & Apelt 1983):

$$\tau_{wu}(t) = \frac{k_1 \rho D}{4} \frac{\partial U}{\partial t} \tag{34}$$

   where k_1 is an empirical coefficient from laboratory experiments, which was found to have different values for accelerating and decelerating flows.
2. Instantaneous material acceleration-based (IMAB) models (Equation (35a)) (e.g., Brunone *et al.* 1991; Bughazem & Anderson 1996; Bergant *et al.* 2001) and its modified counterpart (Equation (35b)) (Pezzinga 2000; Vítkovský *et al.* 2006), which are capable of both accelerating and decelerating flows, respectively:

$$\tau_{wu}(t) = \frac{k_3 \rho D}{4} \left(\frac{\partial U}{\partial t} - a \frac{\partial U}{\partial x} \right) \tag{35a}$$

$$\tau_{wu}(t) = \frac{k_3 \rho D}{4} \left(\frac{\partial U}{\partial t} + \text{sign}(U) a \left| \frac{\partial U}{\partial x} \right| \right) \tag{35b}$$

where k_3 is a coefficient, which can be calibrated from experimental data or simulation data by accurate 2D/3D models.

3. Weighting function-based (WFB) models (e.g., Zielke 1968; Trikha 1975; Vardy & Brown 1995).

$$\tau_{wu}(t) = \frac{4 v_k \rho}{D} \int_0^t W(t - t') \frac{\partial U}{\partial t'} dt' \tag{36}$$

where $t' =$ a dummy variable representing the instantaneous time in the time history; $v_k =$ kinematic viscosity of the fluid; $W(\cdot) =$ weighting function and $W(t) = \alpha \exp(-\beta t)/\sqrt{\pi t}$; $\alpha = D/4\sqrt{v_k}$; $\beta = 0.54 v_k (R_e)^k / D^2$; $k = \log(14.3/(R_e)^{0.05})$; and $R_e =$ the Reynolds number.

2D unsteady friction model

Based on the Boussinesq assumption, the total shear stress in Equation (32) for the quasi-2D and 2D models can be expressed as:

$$\tau = -\rho(v_k + v_t) \frac{\partial u}{\partial r} = -\rho v_T \frac{\partial u}{\partial r} \tag{37}$$

where $v_T = v_k + v_t =$ total viscosity; and $v_t =$ turbulent eddy viscosity. The commonly used 2D turbulence models in transient pipe flows mainly include the following:

1. Quasi-steady algebraic (QSA) models, which are based on the instantaneous velocity distribution (e.g., Wood & Funk 1970; Vardy & Hwang 1991; Silva-Araya & Chaudhry 1997; Pezzinga 1999). The two commonly used 2D turbulence model for transient flows are the five-region model and two-layer model (Ghidaoui *et al.* 2005):
   - Five-region turbulence (FRT) model:
     (a) Viscous layer: $\frac{v_T}{v_k} = 1$ for $0 \leq y_* \leq \frac{1}{a_c}$;
     (b) Buffer I layer: $\frac{v_T}{v_k} = a_c y_*$ for $\frac{1}{a_c} \leq y_* \leq \frac{a_c}{C_B}$;
     (c) Buffer II layer: $\frac{v_T}{v_k} = C_B y_*^2$ for $\frac{a_c}{C_B} \leq y_* \leq \frac{\kappa}{C_B + \kappa^2/4 C_m R_*}$;

(d) Logarithmic region: $\frac{v_T}{v_k} = \kappa y_*[1 - (\kappa/4C_m)(y_*/R_*)]$ for

$$\frac{\kappa}{C_B + \kappa^2/4C_mR_*} \leq y_* \leq \frac{2C_mR_*}{\kappa}\left(1 + \sqrt{1 - C_c/C_m}\right);$$

(e) Core region: $\frac{v_T}{v_k} = C_cR_*$ for $\frac{2C_mR_*}{\kappa}\left(1 + \sqrt{1 - C_c/C_m}\right)$ $\leq y_* \leq R_*;$

where $y_* = \frac{U_Ty}{v_k}$; $R_* = \frac{U_TR}{v_k}$; $U_T = \sqrt{\frac{\tau_w}{\rho}}$; $R = \frac{D}{2}$; $y = R - r$; $U_T = $ the initial friction velocity; and $a_c = 0.19$; $C_B = 0.011$; $\kappa_1 = 0.41$; $C_m = 0.077$; $C_c = 0.06$.

- Two-layer turbulence (TLB) model:
  (a) Viscous sub-layer: $v_t = 0$ for $y_* \leq 11.63$;
  (b) Turbulent region: $v_t = l^2\left|\frac{\partial u}{\partial r}\right|$ for $y_* \geq 11.63$;

  where $l = $ the mixing length, and $l = k_1ye^{-\left(\frac{y}{R}\right)}$; $k_1 = 0.374 + 0.0132\ln\left(1 + \frac{83100}{R_e}\right)$; and other notations defined previously.

(2) Two equation-based (TEB) models, i.e., kinetic energy and dissipation equations (e.g., Zhao & Ghidaoui 2006; Riasi *et al.* 2009; Duan *et al.* 2010a)

  - Liner $\kappa - \varepsilon$ model

$$v_t = C_\mu f_\mu \frac{\kappa^2}{\varepsilon} \tag{38}$$

where $\kappa, \varepsilon = $ turbulent kinetic energy and dissipation rate, respectively, which can be expressed by the two equations below:

$$\frac{\partial \kappa}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(v_k + \frac{v_t}{\sigma_k}\right)\frac{\partial \kappa}{\partial r}\right] + v_t\left(\frac{\partial u}{\partial r}\right)^2 - \varepsilon \tag{39}$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(v_k + \frac{v_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right] + v_tC_{\varepsilon 1}f_1\frac{\kappa}{\varepsilon}\left(\frac{\partial u}{\partial r}\right)^2 - C_{\varepsilon 2}f_2\frac{\varepsilon^2}{\kappa} \tag{40}$$

where $f_w = 1.0 - \exp\left\{-\frac{\sqrt{R_y}}{2.30} + \left(\frac{\sqrt{R_y}}{2.30} - \frac{R_y}{8.89}\right)\left[1 - \exp\left(-\frac{R_y}{20}\right)\right]^3\right\}$; $R_y = \frac{y\sqrt{\kappa}}{v_k}$;

$f_2 = f_w^2\left\{1.0 - 0.22\exp\left[-\left(\frac{R_t}{6}\right)^2\right]\right\}; R_t = \frac{\kappa^2}{v_k\varepsilon}$; $C_\mu = 0.09; \sigma_k = 1.0; \sigma_\varepsilon = 1.3; C_{\varepsilon 1} = 1.39;$ $\qquad f_1 = 1.0$;

$C_{\varepsilon 2} = 1.80$; and $y = R - r$.

Many researchers in the field of transients/waterhammer have investigated the linear $k - \varepsilon$ turbulence model in pipe flows, especially for the near pipe-wall region flows, and developed many different representations of coefficient f_μ in Equation (38) (e.g., Patel *et al.* 1985; Martinuzzi & Pollard 1989; Mankbadi & Mobark 1991; Fan *et al.* 1993; Rahman & Siikonen 2002). One typical representation among these $k - \varepsilon$ models was proposed by Fan *et al.* (1993), which is applicable to both low and high Reynolds flows, and has been successfully used to describe the eddy viscosity in transient pipe flows (Zhao & Ghidaoui 2006):

$$f_\mu = 0.4\frac{f_w}{\sqrt{R_t}} + \left(1 - 0.4\frac{f_w}{\sqrt{R_t}}\right)\left[1 - \exp\left(-\frac{R_y}{42.63}\right)\right]^3 \tag{41}$$

Based on the 1D analytical derivations and 2D numerical simulations, Duan *et al.* (2012a) conducted a systematical analysis on the relevance of unsteady friction (turbulence) with system scales (T_w/T_d or L/D with T_w and T_d being timescales of axial wave propagation and radial turbulent diffusion) and initial flow conditions (fRe_0 with Re_0 being initial Reynolds number). The main results are shown in Figure 6, indicating that the contribution of unsteady friction effect to the damping rate of pressure head peak in practical
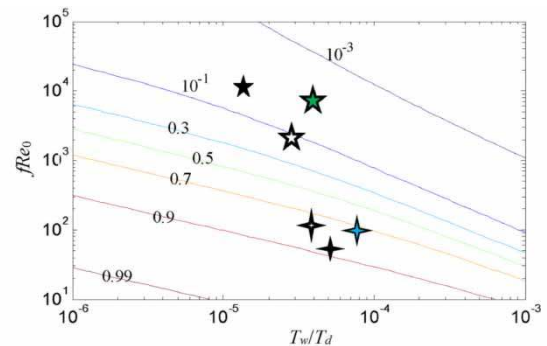
Field Tests: ★ Brunone and Morelli (1999); ★ Brunone et al. (2002); ☆ Stephens et al. (2005)

Lab. Tests: ✚ Holmboe and Roleau (1967); ✚ Pezzinga (2000); ✚ Bergant and Simpson (1994).

Figure 6 │ Relevance of unsteady friction with system scales and initial conditions (*fRe₀* and *Tw/Td*) in water supply pipeline systems.

pipe systems with relatively large time scale ratio (T_w/T_d or L/D) is less important than that is implied by laboratory experiments characterized by relatively small timescale ratio (T_w/T_d or L/D). The findings of that study also imply that the calibrated unsteady friction or turbulence models based on laboratory experimental tests may overestimate the importance and contribution of transient friction effect to transient responses (amplitude damping and peak smoothing) as they are applied to practical pipeline systems. It is concluded from Duan *et al.* (2012a) that it is necessary to perform a full-scale calibration for any unsteady friction or turbulence model when it is first developed and applied to specific pipeline systems.

To address this issue, an effort has been made in Meniconi *et al.* (2014), which is an extension to the former work by Duan *et al.* (2012a), where the time-dependent unsteady viscosity is considered and included in the 1D unsteady friction model. Their application results for different field tests demonstrated the substantial improvement of the unsteady friction simulation for practical pipeline systems with relatively large timescale ratios (T_w/T_d or L/D) and initial Reynolds number (Re_0). Thereafter, Duan *et al.* (2017a) further investigated the mechanisms of different unsteady friction models, including 1D IMAB and WEB models and 2D $\kappa - \varepsilon$ turbulence model, through the local and integral energy analysis. Their results and analysis confirmed again the former conclusion that the importance of unsteady friction effect to the transient envelope attenuation is decreasing with initial flow conditions (Re_0) and pipe scales (L/D). Meanwhile, their results indicated that the relevance of unsteady friction to the system energy dissipation is highly dependent on the unsteady friction model used. In particular, the 1D unsteady friction models (IMAB and WFB) may underestimate the unsteady friction effect in the low frequency domain, while they may overestimate that effect in the relatively high frequency domain. Therefore, a more comprehensive unsteady friction model (e.g., 2D or 3D turbulence model) is required for simulating a long-duration transient pipe flow such as in practical conveyance pipelines.

Viscoelastic model for plastic pipelines

While the modeling of unsteady friction effect has received more and more attention in the study of transient pipe flows, the current transient models coupled solely with those present friction models cannot adequately represent the pressure wave attenuation observed in real-world pipe systems (McInnis & Karney 1995; Ebacher *et al.* 2011). In fact, other than the energy dissipation from the pipe skin roughness (τ_w) and turbulent eddy viscosity (ν_t), viscoelasticity due to the pipe-wall deformation is another important factor affecting the energy change and loss in transients, i.e., ε in Equation (29) and the third term in the continuity Equation (30). The use of viscoelastic pipes is becoming more and more popular in real-life pipeline installation (Triki 2018). The commonly used viscoelastic pipe materials today mainly include PVC, PPR, PE, and HDPE. Therefore, the studies on transient flow behaviors in viscoelastic pipeline become essential and important to meet such practical requirements.

Viscoelastic characteristics of plastic pipes

Recently, numerical and experimental studies have been conducted for viscoelastic responses in plastic or polymeric pipelines in laboratory settings to investigate the possibility of using physical properties of such pipes for suppressing transient oscillations (e.g., Franke 1983; Güney 1983; Ghilardi & Paoletti 1986; Covas *et al.* 2004, 2005b; Ramos *et al.* 2004; Gong *et al.* 2018; Triki 2018; Fersi & Triki 2019; Urbanowicz *et al.* 2020). It has been shown in these studies that the viscoelastic pipes could reduce the magnitude of unsteady fluid oscillations due to the larger capacity for storing strain energy in comparison with elastic pipes. The general behaviors/response of elastic and viscoelastic pipe materials during the external loading and unloading processes are sketched in Figure 7 (Meyers & Chawla 2008).

In Figure 7(a), the energy stored in the elastic material due to external loads can be expressed as Area-I, while that for viscoelastic material is shown as Area-II. Under the same external load, σ_0, the energy Area-II of the viscoelastic pipeline is much larger than the energy Area-I of elastic pipeline and the deformation of viscoelastic pipes (ε_2) is therefore much larger than that of elastic pipes (ε_1). From Figure 7(b), the loading path ('O–A') for elastic pipes and the unloading (relaxation) path ('A–O') are nearly on the top of each other with following approximately a linear behavior but in the opposite direction. That is, the pressurized state could be recovered immediately once the
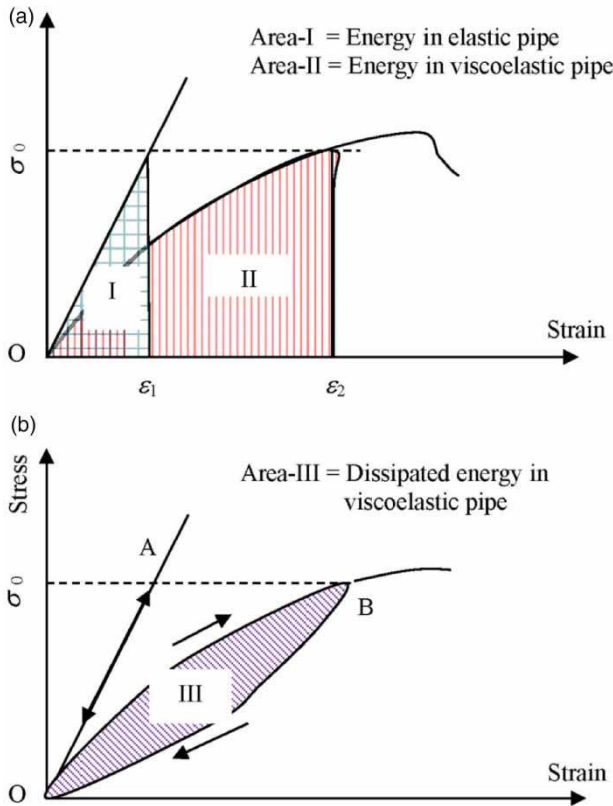
Figure 7 | Stress–strain curves for elastic and viscoelastic pipe materials: (a) energy storage capacity; (b) paths of loading and unloading processes.

external load is removed. However, for the viscoelastic material of plastic pipe-wall, the relaxation path ('B–O') is very different from the loading path ('O–B') and both paths behave nonlinearly, forming a 'hysteresis' loop with energy dissipation as shown in the energy Area-III of Figure 7(b) (Meyers & Chawla 2008; Love 2013). This kind of material property will lower the wave speed in viscoelastic pipes. As a result, the viscoelastic pipe would have a longer pipe characteristic time and a slower transient response, so that a given maneuver duration may result in relatively faster operation within the transient response for plastic pipes compared to elastic pipe cases. Meanwhile, the viscoelastic pipes could likely withstand a more serious pressure surge situation than the elastic pipe since the transients can be 'smoothed' out and fade away quickly due to the energy storage and dissipation of the viscoelastic materials in plastic pipelines. It is also noted that the response in Figure 7 is based on an ideal viscoelastic model, and experimental examples may refer to Covas *et al.* (2004).

Modeling of viscoelastic behavior in transients

The K-V model has been commonly adopted to model the material viscoelasticity in pipe fluid transients due to its accurate representation of the creep and retardation effect and its simple form of expression (Güney 1983; Covas *et al.* 2005b). The creep function of viscoelastic pipe material can be expressed by:

$$J(t) = J_0 + \sum_{kv=1}^{N} [J_{kv}(1 - e^{-t/\tau_{kv}})] \tag{42}$$

in which $J_{kv} = 1/E_{kv} =$ creep compliance of the kv-element; $E_{kv} =$ modulus of elasticity of the kv-element; $\tau_{kv} = \eta_{kv}/E_{kv} =$ retardation time of the kv-element; $\eta_{kv} =$ viscosity of the kv-element; $N =$ total number of K-V elements. By considering the time convolution effect, the retarded strain of pipes in the continuity Equation (30) can be expressed mathematically by:

$$\varepsilon_r(x, t) = \int_0^t \left(\sigma(x, t - t') \frac{\partial J(t')}{\partial t'} \right) dt' \tag{43}$$

in which $\sigma(x, t) =$ normal stress related to pressure head. As a result, a linearized expression of the viscoelastic deformation rate can be obtained as (Güney 1983):

$$\frac{\partial \varepsilon_r}{\partial t} = \sum_{kv=1}^{N} \left(\frac{J_{kv}}{\tau_{kv}} F_v(x, t) - \frac{\varepsilon_{r_{kv}}(x, t)}{\tau_{kv}} \right) \tag{44}$$

where $F_v(x, t) = C_1 \Delta P(x, t)$; $\Delta P(x, t) = P(x, t) - P_0(x)$, and $P(x, t) =$ instantaneous pressure at time t; $P_0(x) =$ initial pressure; $C_1 = \dfrac{CD}{2e}$, and $C =$ pipe constraint coefficient; $e =$ pipe-wall thickness; $\varepsilon_{r_{kv}}(x, t) =$ retarded strain of kv-element, calculated by the following approximation:

$$\varepsilon_{r_{kv}}(x, t) = J_{kv} F_v(x, t) - J_{kv} e^{-\Delta t/\tau_{kv}} F_v(x, t - \Delta t) + e^{-\Delta t/\tau_{kv}} \varepsilon_{r_{kv}}(x, t - \Delta t)$$
$$- J_{kv} \tau_{kv}(1 - e^{-\Delta t/\tau_{kv}}) \frac{F_v(x, t) - F_v(x, t - \Delta t)}{\Delta t} \tag{45}$$

Therefore, the viscoelastic term in the transient model (continuity equation) can be implemented easily in the discrete scheme, e.g., the method of characteristics (MOC),

so as to obtain numerically the transient responses in visco-elastic pipes.

The application results of the studies by Covas *et al.* (2005b) and Ramos *et al.* (2004) demonstrated that the viscoelastic effect is much more dominant than the unsteady friction effect on pressure wave peak attenuation. Moreover, in addition to peak attenuation, the viscoelastic effect induces a time-delay or phase-shift in transient responses and this behavior can never be captured by considering only the unsteady friction or turbulence in the transient process. However, extensive numerical simulations conducted in Covas *et al.* (2005b) also indicated that the calibrated creep compliance coefficients for the viscoelastic K-V model are clearly affected by the initial flow conditions (e.g., Q, H, and Re_0). On this point, Covas *et al.* (2005b) reasoned that these non-physical results are due to inaccurate capture of the unsteady friction effect by 1D quasi-steady models for transient flows in their study.

To address this issue, the study of Duan *et al.* (2010a) developed a quasi-2D model, by coupling the 1D K-V model and 2D $\kappa - \varepsilon$ turbulence model, in order to accurately represent both the unsteady friction (turbulence) and viscoelasticity in plastic pipe transients. Their application results revealed the relative independence of calibrated viscoelastic parameters in the K-V model on the initial flow conditions in the same system. That is, by using their developed quasi-2D model, a set of unified viscoelastic parameters could be obtained for the same plastic material pipeline system. Meanwhile, the energy analysis performed in Duan *et al.* (2010b) indicated that the mechanism of pipe-wall viscoelasticity on affecting transient responses (amplitude damping and phase shifting) is totally different from that of unsteady friction. To be specific, the interaction process of transient waves with pipe-wall viscoelasticity is actually an energy transfer process during each wave period, in which part of the stored energy in the pipe-wall is dissipated due to the viscoelastic material deformation, as shown in Figure 7(b). That is, the fluid wave energy is initially transferred and stored in the pipe-wall (due to pipe expansion) during the positive wave cycle, which is then returned to fluid waves during the subsequent negative wave cycle (due to pipe contraction). However, the returned energy will be smaller than the originally stored amount, which is described as the energy dissipation by the hysteresis shown in Figure 7(b).

Furthermore, many researchers have focused on the calibration process of viscoelastic parameters in the K-V model for better representing the transient responses of different plastic pipes. For instance, Keramat & Haghighi (2014) proposed a time-domain transient-based straightforward method for the identification of viscoelastic parameters. An FSI model was developed by Zanganeh *et al.* (2015) to represent the interaction of viscoelastic pipe-wall with transient waves. Ferrante & Capponi (2018a) examined the viscoelastic parameter calibration for a branched plastic pipeline system based on the time-domain analysis method, followed by another study on the influence of the number of K-V elements on the model accuracy (Ferrante & Capponi 2018b). Gong *et al.* (2016) developed a frequency shift-based method for determining the viscoelastic pipe parameter. Frey *et al.* (2019) presented a phase and amplitude-based characterization method in the frequency domain for calibrating the viscoelastic parameters and their influences on transient responses. Recently, Pan *et al.* (2020) proposed an efficient multi-stage frequency domain method for simultaneously determining both the number and values of the viscoelastic parameters. All these calibration methods have been validated through different experimental tests in the literature.

In addition to the K-V model, some other viscoelastic models have been examined for the modeling of transient flows in plastic pipes. For example, Ferrante & Capponi (2017) investigated three types of viscoelastic models (i.e., Maxwell model, standard linear solid model, and generalized Maxwell model) for both HDPE and PVC-O pipe systems. Their results revealed that each of these models may present different advantages and limitations in terms of accuracy and efficiency for different pipeline systems. Based on these developed viscoelastic models and calibration methods, the transient theory and model have been successfully extended and applied to plastic pipelines, and thereby the development of transient-based methods for viscoelastic pipeline diagnosis in UWSS, which will be further introduced later in this paper.

Time-domain numerical simulation

In the time domain, due to the non-linear property of the shear stress (friction) in momentum Equation (25) or (28) and the complex boundary conditions in UWSS, it is impossible to

directly obtain the general analytical solutions for the governing equations of transient pipe flows. To this end, different numerical schemes have been commonly developed and used to obtain approximate solutions, such as finite difference, finite volume, finite element, and others (e.g., Joukowsky 1904; Angus 1935; Amein & Chu 1975; Rachford & Ramsey 1977; Katopodes & Wylie 1984; Chaudhry & Hussaini 1985; Suo & Wylie 1989). Among these methods, the MOC is one of the commonly used schemes for solving 1D or 2D transient models in the literature (Lister 1960; Wiggert & Sundquist 1977; Wylie *et al.* 1993; Ghidaoui & Karney 1994; Karney & Ghidaoui 1997; Ghidaoui *et al.* 1998; Chaudhry 2014; Nault *et al.* 2018). For the review purpose, the implementation of MOC for 1D and 2D models are summarized as follows.

The principle of the MOC is to convert original partial differential equations (PDEs) into the ordinary forms (ODEs). In 1D models, the MOC scheme introduces two characteristic lines (lines *A–P* and *B–P*) as shown in Figure 8(a) and the unknowns at point *P* are calculated from the known quantities at points *A* and *B* obtained from the previous time step. Mathematically, the converted ODEs are shown as follows:

$$H_p = C_A - B_A Q_p$$
$$H_p = C_B + B_B Q_p \tag{46}$$

where

$$C_A = H_A + Q_A[B - R|Q_A|(1 - \eta)]$$
$$B_A = B + \eta R|Q_A|$$
$$C_B = H_B - Q_B[B - R|Q_B|(1 - \eta)] \tag{47}$$
$$B_B = B + \eta R|Q_B|$$

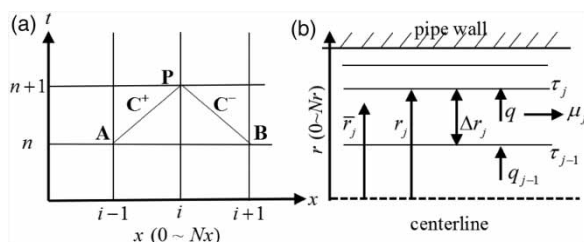$$B = \frac{a}{gA}, \quad R = \frac{f\Delta x}{2gDA^2} \tag{48}$$

Figure 8 | Schematic for MOC scheme: (a) axial direction; (b) radial direction.

in which η is the weighting coefficient, and $\eta = 0.5$–1.0 for achieving numerical stability.

Similarly, for the 2D model, the ODE forms are (Vardy & Hwang 1991):

$$\frac{dH}{dt} \pm \frac{a}{g}\frac{du}{dt} = -\frac{a^2}{g}\frac{1}{r}\frac{\partial q}{\partial r} \pm \frac{a}{g}\frac{1}{r\rho}\frac{\partial(r\tau)}{\partial r},$$

along $\dfrac{dx}{dt} = \pm a$ \hfill (49)

where $q = rv$ is the unit flowrate in the radial direction. In the 2D model, a matrix form will be formed for the whole pipeline system, and all the unknowns (H, u, q) for each time step (e.g., Figure 8(b)) are solved by using the MOC scheme and finite difference (FD) scheme (Wiggert & Sundquist 1977; Vardy & Hwang 1991). To improve the computational efficiency of the 2D MOC results, Zhao & Ghidaoui (2003) have developed a decomposed matrix form for the above ordinary differential equations (ODEs) as:

$$\mathbf{BU} = \mathbf{b_u} \tag{50}$$

$$\mathbf{CV} = \mathbf{b_v} \tag{51}$$

in which: $\mathbf{V} = \{H_i^{n+1}, q_{i,1}^{n+1}, \cdots, q_{i,j}^{n+1}, \cdots, q_{i,Nr-1}^{n+1}\}^T$; $\mathbf{U} = \{u_{i,1}^{n+1}, \cdots, u_{i,j}^{n+1}, \cdots, u_{i,Nr}^{n+1}\}^T$; Nr is the total grid in the radial direction; $\mathbf{b_u}$ and $\mathbf{b_v}$ are known vectors which depend on the hydraulic parameters at time level n, and $\mathbf{B}$ and $\mathbf{C}$ are $Nr \times Nr$ tri-diagonal matrices depending on the system conditions and results from previous time steps. From this mathematic manipulation, the central processing unit (CPU) calculation time can be greatly reduced to nearly $1/Nr^2$ of the original calculation time. Thereafter, this efficient model has been further extended in Duan *et al.* (2009) to more complex situations (e.g., multiple-pipe junctions). For example, the matrices for the branched pipe junctions are shown as follows:

$$\mathbf{RH} = \mathbf{S} \tag{52}$$

$$\mathbf{LQ} = \mathbf{W} \tag{53}$$

$$\mathbf{Kq} = \mathbf{J} \tag{54}$$

where: $\mathbf{H} = \{H^{n+1}, \sum_{j=1}^{Nr} Q_j^{n+1}\}^T$; $\mathbf{Q} = \{Q_{p,1}^{n+1,O1}, Q_{p,1}^{n+1,O2}, \cdots,$ $Q_{p,j}^{n+1,O1}, Q_{p,j}^{n+1,O2}, \cdots, Q_{p,Nr}^{n+1,O1}, Q_{p,Nr}^{n+1,O2}\}^T$; $\mathbf{S}$, $\mathbf{J}$, $\mathbf{W}$ and $\mathbf{R}$, $\mathbf{L}$,

$\mathbf{K}$ = the known vectors and matrices based on the system conditions and previous time step results.

Frequency-domain transfer matrix analysis (TMA)

The transfer matrix analysis (TMA) of a transient flow system is to derive the linearized frequency-domain equivalents of the original time-domain momentum and continuity equations in Equations (28) and (30), which describe the transient behavior of the system in the frequency domain. The general form of the transfer matrix for an intact pipe section is (Lee *et al.* 2006; Duan *et al.* 2011a, 2012b; Chaudhry 2014):

$$\left\{ \begin{matrix} q \\ h \end{matrix} \right\}^{n+1} = \begin{bmatrix} \cos(\mu L) & i\frac{1}{Y}\sin(\mu L) \\ iY\sin(\mu L) & \cos(\mu L) \end{bmatrix} \left\{ \begin{matrix} q \\ h \end{matrix} \right\}^{n} \tag{55}$$

where $\mu = \frac{\omega}{a}\sqrt{1 - i\frac{gAR}{\omega}}$; $Y = -\frac{a}{gA}\sqrt{1 - i\frac{gAR}{\omega}}$; $R = \frac{fQ}{gDA^2}$; q, h = discharge (Q) and pressure head (H) in the frequency domain; n = point under consideration; L = pipe section length; ω = frequency; i = imaginary unit. This matrix equation relates the head and discharge perturbations on either ends of a section of intact single pipeline. Similar matrices describing other system elements can be derived and combined with Equation (55) to produce the overall matrix describing the system. Elements with external forcing will require the matrix to be expanded into a 3×3 matrix and the final system matrix is in the following form (Lee 2005; Chaudhry 2014):

$$\left\{ \begin{matrix} q \\ h \\ 1 \end{matrix} \right\}^{n+1} = \begin{bmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{bmatrix} \left\{ \begin{matrix} q \\ h \\ 1 \end{matrix} \right\}^{n} \tag{56}$$

where U_{ij} is the system matrix element.

For illustration, the transient responses of water supply pipeline systems with different configurations (e.g., single, series and branched pipe systems) obtained by the time-domain MOC scheme and frequency-domain TMA method are plotted in Figure 9(a) and 9(b), respectively (Duan *et al.* 2011a; Duan 2018).
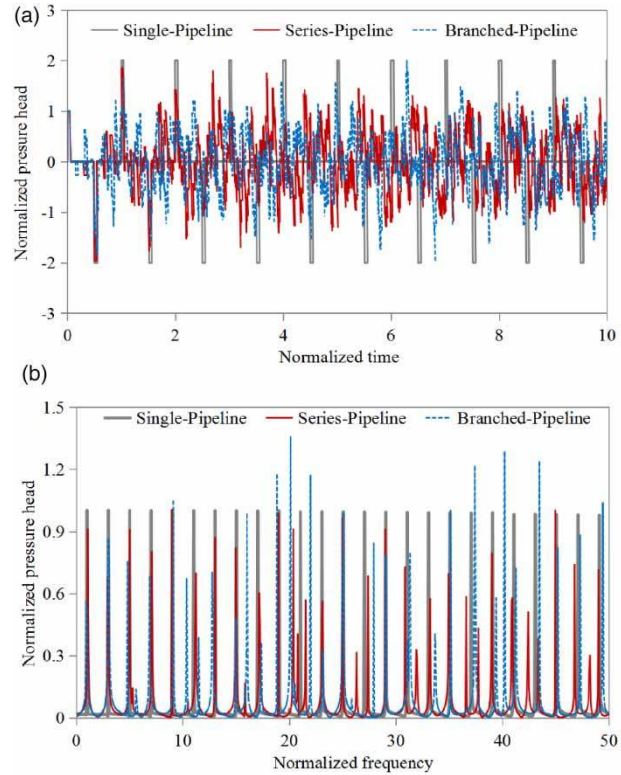

Figure 9 │ Transient responses of different pipeline systems: (a) time-domain results by MOC; (b) frequency-domain results by TMA.

The comparison of different results in Figure 9 demonstrates: (i) the significant influences of system complexities (different junctions) on the transient responses in both time and frequency domains (Meniconi *et al.* 2018); and (ii) the different dependences of transient responses on the system configurations between the time- and frequency-domain results. Specifically, compared to time-domain results, the influences of pipe junctions to the transient responses by the TMA become relatively simple and independent for different resonant peaks, which have similar impact complexities that are not superimposed or accumulated with frequency, as shown in Figure 9(b).

It is also worth noting that the linearization approximation has been applied in the mathematical derivations to obtain the above transfer matrix, such as nonlinear turbulent friction and external orifice flows in the system. On this point, the influence and error of such linearization have been systematically examined in the literature (e.g., Lee & Vítkovský 2010; Lee 2013; Duan *et al.* 2018). Their results indicated that this linearization approximation becomes valid with acceptable

accuracy for transient modeling and analysis, as long as the perturbation of transient flows is relatively small to the initial steady state flows (e.g., $q \ll Q_0$). Meanwhile, the study by Duan *et al.* (2018) has provided an iterative solution for the transfer matrix analysis, so as to include the nonlinear turbulent friction term (e.g., Equation (31)).

Due to the explicit and relatively simple dependent relationship of transient responses on the system information (pipeline conditions, devices, and system states) in the frequency domain (e.g., Figure 9(b)), the transfer matrix analysis (TMA) has been widely used for developing the transient-based pipe diagnosis methods in the literature, such as leakage, different junctions partial blockage detection (Lee 2005; Duan 2011, 2017; Lee *et al.* 2013b; Che 2019).

TRANSIENT-BASED DEFECT DETECTION (TBDD) METHODS

While many practicing engineers think most often about transients with reference to their negative or damaging physical effects on a pipe system, or deterioration of potable water quality, etc., there is a positive aspect to transients as an integrity management tool (Wylie *et al.* 1993; Duan *et al.* 2010d; Chaudhry 2014). In fact, transients have the ability to acquire and transmit a significant range and variety of system information along the pipeline while traveling through the system at high speeds. This high-speed transmission of information can be utilized in many practical applications, such as leak and partial blockage detection and pipeline condition monitoring. This is also the underlying physics and principle for developing different transient-based defect detection (TBDD) methods in the literature.

In the past two decades, transient pressure waves have been widely used for the detection of different pipe defects or anomalies (especially for leaks) by many researchers (e.g., Brunone 1999; Vítkovský *et al.* 2003; Covas *et al.* 2005a; Lee *et al.* 2006; Stephens 2008; Covas & Ramos 2010; Duan *et al.* 2011a, 2012b, 2014a; Ghazali *et al.* 2012; Gong *et al.* 2013a; Xu & Karney 2017; Kim 2018, 2020; Duan 2020). This transient-based method has been regarded as a promising way for detecting pipe anomalies because it has desirable merits of high efficiency, low cost, and non-intrusion (Gupta & Kulat 2018). The tenet of the TBDD method

is that an injected transient wave propagating in a pipeline is modified by, and thus contains information on, properties and states of the pipeline. Potential pipe anomalies can be detected by actively injecting waves and then measuring and analyzing data at the accessible points in the system (e.g., fire hydrants) (Lee 2005; Stephens 2008; Duan 2011).

In this section, the progress and achievement of the TBDD methods are reviewed and summarized according to their detection contents (different types of pipe defects) and application methods (different utilizations of transient information) in UWSS.

Transient-based leak detection

Although it has been reported that not all of the water loss attributes to pipe leaks and bursts (as shown in Figure 2), leakage in the pipe system may be one of the main causes according to the reports of the International Water Supply Association (IWSA) (Lambert 2002). Leakage under pressurized state and the infiltration under unpressurized state from the surrounding environment in the UWSS (e.g., Figure 1(a)) can damage the surrounding environment (soil washing and foundation scouring) and can also cause potentially an increase of public health risks (water contamination and air/solid intrusion) (Burn *et al.* 1999). These practical problems have stimulated the development of many leak detection techniques in the past decades (Wang 2002). Among the various leak detection methods, the transient-based leak detection method has especially attracted the attention of researchers recently (Colombo *et al.* 2009; Ayati *et al.* 2019). In the following, five types of transient-based methods are reviewed briefly (Colombo *et al.* 2009; Duan *et al.* 2010c), including transient reflection-based method (TRM), transient damping-based method (TDM), transient frequency response-based method (TFRM), inverse transient analysis-based method (ITAM), and signal processing-based method (SPM).

Transient reflection-based method (TRM)

The TRM is the easiest to apply among the five types of leak detection method. It evaluates the presence of a leak and locates the leak in the pipeline by utilizing the reflection information of the pressure signal. Brunone (1999)

introduced the method with the following equation:

$$x_L^* = \frac{a}{2L}(t_2 - t_1) \tag{57}$$

where x_L^* = dimensionless leak location that represents the leak distance from the downstream boundary (x_L) normalized by pipe length; L = length of pipe section under investigation; t_1 = time instant at which the pressure wave generated at the end valve arrives at the measurement location; and t_2 = time instant at which the reflected wave at the leak reaches the measurement location. The leakage quantity (leak size) can be evaluated by the orifice equation:

$$Q_L = C_d A_L \sqrt{2g(H_L^t - H_{OL}^t)} \tag{58}$$

where Q_L = leak discharge; C_d = leak size coefficient; A_L = leak area size; H_L^t = instant internal pressure head at leak location; and H_{OL}^t = instant external pressure head at leak location. Note that the leak size in Equation (58) can be calculated by combining the numerical MOC for waterhammer governing equations (see details in Brunone (1999)). Brunone & Ferrante (2001) further studied the applicability of the TRM for leak detection and estimation in pressurized single pipes by experimental validation. Their results showed that the leak location can be accurately predicted by measuring the arrival times of the signal reflections.

To better identify the transient reflection information from the measured data traces, different algorithms have been adopted to achieve transient signal analysis in the literature, such as impulse response function (IRF) (Liou 1998; Kim 2005; Lee *et al.* 2007; Nguyen *et al.* 2018), wavelet analysis (Ferrante & Brunone 2003a, 2003b; Ferrante *et al.* 2007, 2009a, 2009b), and cumulative sum (CUSUM) (Misiunas *et al.* 2005; Bakker *et al.* 2014). It has been evidenced from these studies that the use of these algorithms has substantially enhanced the application of the TRM.

Transient damping-based method (TDM)

While the TRM relies solely on the reflection information within transient traces, an alternative method has been developed to work solely on the damping rate of the

transient signal (Wang *et al.* 2002; Brunone *et al.* 2019; Capponi *et al.* 2020). The TDM was first proposed in Wang *et al.* (2002) and utilizes the relative damping rates of the first two harmonic frequency components in the transient trace to locate the leak. This method was derived analytically from the 1D transient model for a single pipe system. The equation relating the harmonic damping ratios and the leak location is:

$$\frac{R_{n_1 L}}{R_{n_2 L}} = \frac{\sin^2(n_1 \pi x_L^*)}{\sin^2(n_2 \pi x_L^*)} \tag{59}$$

$$C_d A_L == \frac{R_{nL} A \sqrt{2gH_{L0}}}{a \sin^2(n \pi x_L^*)} \tag{60}$$

where R_{nL} = the leak-induced damping rate for the nth mode; C_d = leak coefficient; n = any mode of n_i; and n_i = mode number, with i = 1 or 2.

Based on this method in Equations (59) and (60), the leaks can be found through the inspection of the results of different mode amplitude ratios. For example, in the simple pipe system shown in Figure 10(a), if a small leak (e.g., 10% of pipe discharge) is placed at 60% of the pipe length distance from the upstream tank (i.e., $x_L = 0.4L$), the leak information appears in Figure 10(b) as the difference between the transient pressure head traces with and
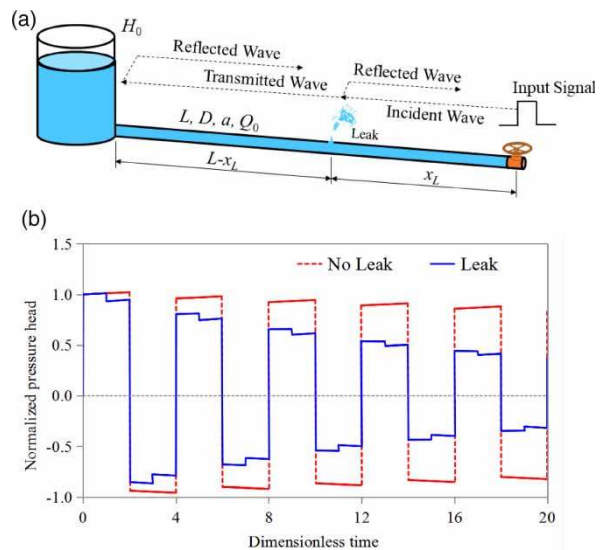

Figure 10 | Pipe system for illustration: (a) pipeline with a leak; (b) transient pressure head at downstream valve (1D numerical results).

without leakage in the pipeline. The results show clearly that the damping for the leak case is much faster than that for the no-leak case. By using Wang's method (Wang *et al.* 2002), the damping rates of different frequency modes for cases with and without leakage are shown in Figure 11(a) and 11(b), respectively, which finally can provide the prediction of leaks in the system according to Equations (59) and (60).

To obtain the results of Equations (59) and (60) for the TDM in Wang *et al.* (2002), the key assumptions imposed for analytical derivations include (Nixon *et al.* 2006):

1. linearization of turbulent friction term;
2. relatively small amplitude of transient event;
3. relatively small size of leak relative to the main flowrate;
4. single pipeline system configuration.

These assumptions have been discussed and verified in Nixon *et al.* (2006) by using a 2D transient model. Their study showed that the assumptions do not limit the applicability of the TDM developed in Wang *et al.* (2002) model in practice provided that the system is simple and the friction damping effect can be represented correctly in pressure head traces. Owing to the last assumption, the TDM is restrictive to multiple-pipeline systems since the complex initial and boundary conditions are still difficult to incorporate into this method if the studied water distribution system is not simplified (Capponi *et al.* 2020). However, Nixon *et al.* (2006) also pointed out that the TDM in Wang *et al.* (2002) could be applied to practical complex systems by isolating the individual pipelines from the rest of the system.

Meanwhile, to address the influence of transient friction and turbulence, a 2D form of the TDM was successfully derived by Nixon *et al.* (2006). The incorporation of the constant viscosity formula in the 2D transient model provides the feasibility of qualitative evaluation of 2D turbulence (unsteady friction) effect on the transient-based leak detection. The detailed form can be expressed as below:

$$\frac{n\pi R}{L}\sum_{k=1}^{\infty}\left(\frac{u_{nk}(t)}{\alpha_k^*}J_{B1}(\alpha_k^*)\right) - \frac{gR}{2a^2}\frac{d\tilde{h}_n}{dt} - \frac{gf'_{bc}(t)R}{n\pi a^2}(-1)^{n+1}$$
$$= \gamma + \frac{2\eta_c}{L^2}f_{bc}(t)x_L\sin\frac{n\pi x_L}{L} + \frac{2\eta_c}{L}\tilde{h}(x_L,t)x_L\sin\frac{n\pi x_L}{L} \quad (61)$$

or in matrix form,

$$\frac{d\mathbf{u}}{dt} = \mathbf{B}_1\mathbf{u} + \mathbf{C}_1\mathbf{f} \quad (62)$$

where $J_{B1}(\cdot) =$ the Bessel function; $\alpha_k^* =$ roots of the equation of $J_{B0}(\alpha_k^*) = 0$, and $J_{B0}(\cdot)$ is the Bessel function of the first kind of order zero; $f_{bc}(\cdot) =$ boundary conditions in 2D derivation; $R =$ pipe radius; $\tilde{h} = h - xf(t)/L =$ the auxiliary function; $x_L =$ leak location; γ, $\eta_c =$ the coefficients of the linearized leak term in the model, which can be calculated as:

$$\gamma = \frac{C_d A_L\sqrt{2g}}{2\pi R}\sqrt{(H_{L0} - z_L)}$$

$$\eta = \frac{C_d A_L\sqrt{2g}}{2\pi R}\frac{1}{2\sqrt{(H_{L0} - z_L)}}$$

in which H_{L0}, $z_L =$ original head and elevation at leak location; $\mathbf{u} = [\tilde{h}_1, \tilde{h}_2, \cdots, \tilde{h}_N, u_{11}, u_{12}, \cdots u_{NK}]$; and $\mathbf{B}$, $\mathbf{C} =$ coefficient matrices. As a result, the real parts of the
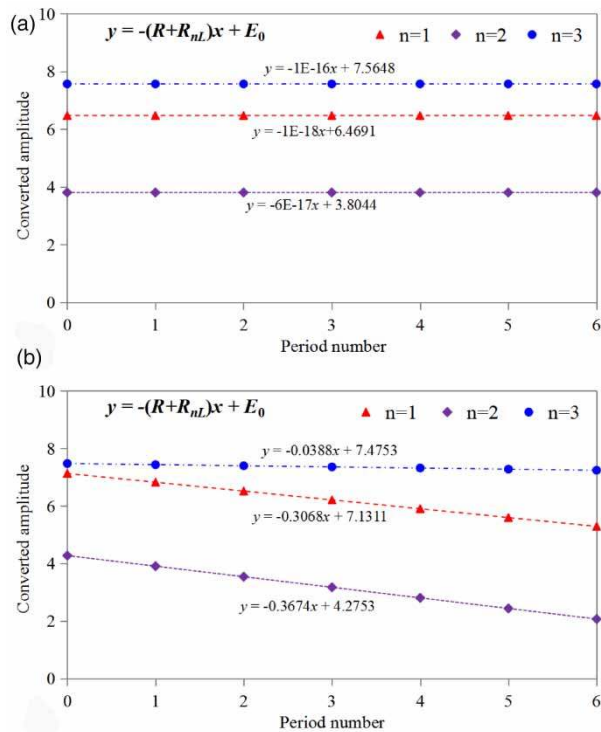

Figure 11 | Results of damping rates for different modes: (a) without leak; (b) with leak.

complex eigenvalues of matrix **B** represent the damping rates of the given transient information.

Transient frequency response-based method (TFRM)

The transient reflection- and damping-based methods were designed to use only one of the two types of information in the transient signal for detecting and locating leaks. There are other methods, such as the transient frequency response-based method (TFRM) that uses the entire transient signal to detect and locate the leaks. In this type of method, the leak can be identified and located in the system by analyzing the harmonic and impulse modes of pressure wave traces (Ferrante & Brunone 2003a, 2003b; Covas *et al.* 2005c; Lee *et al.* 2006, 2007; Sattar & Chaudhry 2008; Duan *et al.* 2011a, 2012c; Gong *et al.* 2013b, 2014a; Kim 2016; Duan 2017). For illustration, the TFRM presented in Lee *et al.* (2006, 2007) and Duan *et al.* (2011a) is introduced herein for the method principle and application procedure.

In any pipeline system, as shown in Figure 12, a transient signal can be considered as the result of different disturbances imposed on the system, e.g., input $Q(t)$, while the measured system responses are the outputs from the system, $H(t)$. In this way, the behavior of a pipeline system can be described as a transfer function that produces the outputs for given inputs. The relationship between input and output signals in the time domain is given as a convolutional integral (Lee *et al.* 2007):

$$H(t) = \int_0^t Q(t)I(t - t')dt' \tag{63}$$

where $I(\cdot) =$ the impulse response function (IRF) of the system containing all the information pertaining to the behavior of the system. By applying the Fourier transform technique (Kreyszig *et al.* 2008), the expression becomes,

$$h(\omega) = q(\omega)F(\omega) \tag{64}$$

where $F(\cdot) =$ the frequency response function (FRF) of the system; $\omega =$ wave frequency.

The system response function, either in the time domain as the IRF or in the frequency domain as the FRF, describes the fundamental response of the system from an impulse excitation. A leak in the pipeline results in a change in this system response. Taking again the simple pipe system in Figure 9(a) for example, the FRF from leaking and non-leaking pipelines are shown in Figure 13(a). In an intact pipeline the FRF consists of a series of uniformly spaced and sized harmonic peaks (thin solid line in Figure 13(a)). On the other hand, for a leaking system the size of these peaks varies with frequency (thick solid line in Figure 13(a)) and was called the 'leak-induced pattern' by Lee *et al.* (2006) and Duan *et al.* (2011a). The responses of the relative amplitude for the first four peak frequency modes with a leak at different locations along the pipeline are shown in Figure 13(b). Then the entire domain along the pipeline can be divided into different zones in which there is unique relation among different frequency peak responses.

This perturbation pattern is the result of leak-induced changes to the transient response and can be used to locate the leaks. Thereafter, the analytical expression for the leak-induced pattern has been widely developed and applied for leak detection in both elastic and viscoelastic pipelines (Lee *et al.* 2006; Duan *et al.* 2012c) with the following form:

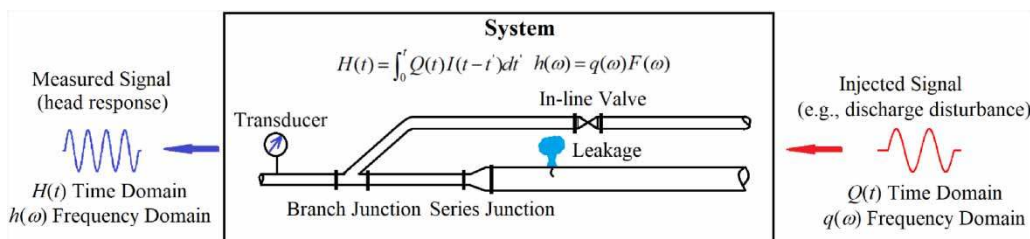$$\hat{h} = \alpha_s \cos(2\pi m x_L^* - \theta) + \beta \tag{65}$$

Figure 12 | Sketch of transient frequency response analysis for a pipeline system.
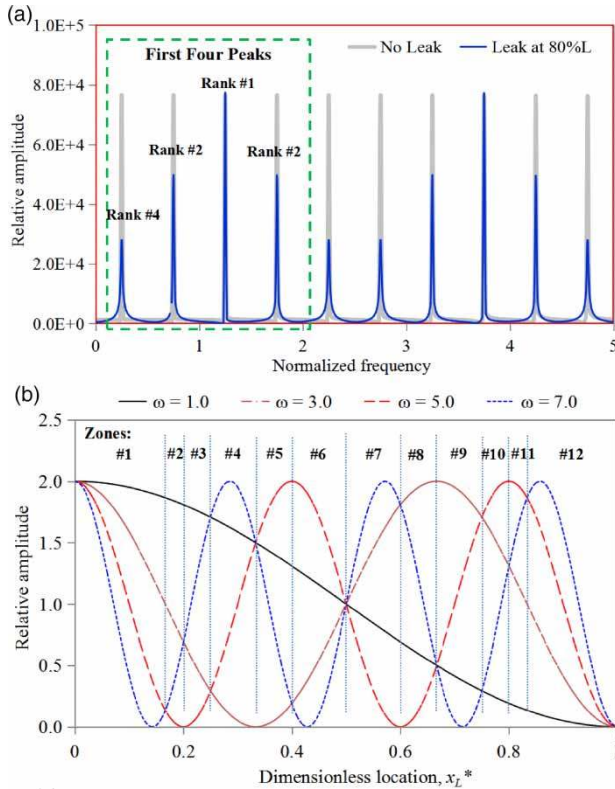
Figure 13 | Transient frequency response results (based on 1D numerical results): (a) FRF in the frequency domain; (b) response pattern for different frequency modes.

where $\hat{h}$ = inverted FRF magnitude; θ, β = coefficients; and m = peak number. The variables x_L^* and α_s in Equation (65) are measures of the potential leak location and size in the system.

From Lee et al. (2006), the TFRM agrees well with experimental results. As the technique uses the entire transient signal, the TFRM technique utilizes both the reflection and damping information from the leak. But there are several aspects that still need more in-depth validations which may include the influences of the transient amplitude, external transient noise, and unsteady friction, among others. It is important to note that this developed TFRM for leak detection does not rely on the system to be driven to resonance by a continuous valve oscillation at the natural system frequency. That is, a continuous valve oscillation at each frequency is not required to build the frequency response function as in Figure 13(a). Instead the technique observes the response of the harmonic frequency components contained in the initial input signal, which can be any signal with sufficient bandwidth including the signal from a fast

valve closure (Lee et al. 2015). The frequency components corresponding to an odd integral multiple of the natural system frequency are reinforced by the system and forms the 'frequency peaks' in Figure 13(a).

The initial form of the TFRM was developed in Lee et al. (2006) for single pipeline situation only, which has greatly limited the applicability of this efficient and economic method. To this end, the study of Duan et al. (2011a) has successfully extended this method to multiple pipes in series, in which the analytical expression of leak-induced pattern has been derived in multiple pipe systems for leak detection. Thereafter, Duan (2017) has further extended this TFRM to more complex pipe systems, including simple branched and looped pipe junctions as shown in Figure 14. As a result, this TFRM has been greatly enhanced for its applicability and efficiency. Specifically, the derived patterns for the branched and looped pipeline systems are given as follows (Duan 2017).

1. For branched pipelines:

$$\hat{h}_{Lnp}^B = \frac{K_L}{C_{np}^B}[1 - \cos(2\mu_{np}x_{Lnp} + \varphi_{np}^B)] \tag{66}$$

where $\hat{h}_{Lnp}$ is the converted TFR based on the difference between the intact and leakage situations in branched pipeline system; np is the number of pipe that the potential leakage is located; x_{Lnp} is the distance of leakage location from the upstream end of the pipeline np; K_L is the impendence factor for describing the leakage size; the subscript L is used for quantity for leaking pipe system; the superscript B indicates the quantity for
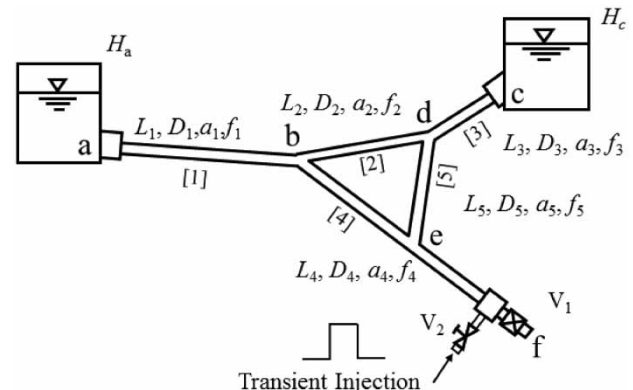

Figure 14 | An illustrative pipe network with branched and looped junctions.

branched pipeline system, and C, ϕ are intact system-based known coefficients.

2. For looped pipelines:

$$\hat{h}_{Ln}^{O} = \frac{K_L}{C_n^O}\left[R_n^O + \sqrt{(S_n^O)^2 + (T_n^O)^2}\sin\left(\mu_n l_n - 2\mu_n x_{Ln} + \varphi_n^O\right)\right]$$

(67)

where the superscript O indicates the quantities obtained for the looped pipeline system; and C, R, S, T, ϕ are known coefficients based on intact system; other symbols are the same as in Equation (66). This extended TFRM has been validated through different numerical simulations (Duan 2017), followed by a systematical investigation based on sensitivity analysis in Duan (2018). The application results in Duan (2017) demonstrated the applicability and accuracy of the extended TFRM method for leakage identification and detection in these multiple-pipeline systems. However, the results also implied that this method is more accurate to locate the pipe leakage than to size the leakage from the applications. Moreover, the results and analysis in Duan (2018) indicated that the uncertainty of the pipe wave speed, diameter and data measurement can contribute dominantly to the variability of the detection results (both leak size and leak location), and the variation of the detection results is more sensitive to the actual leak size than the leak location, which is consistent with the original TFRM for single pipeline systems. From these studies, it can be concluded that a good understanding of the intact pipeline system as well as an accuracy measurement system will be crucial to the application of the TFRM for practical UWSS diagnosis and management.

Inverse transient analysis-based method (ITAM)

The ITAM is a popular method which uses the entire transient signal by calibrating and matching the outputs from a numerical model to measured data records (e.g., Liggett & Chen 1994; Vítkovský *et al.* 2000; Al-Khomairi 2008; Shamloo & Haghighi 2009; Covas & Ramos 2010; Capponi *et al.* 2017). The predicted response with the leaks in the correct locations results in the closest match with the measured results. Since the ITAM uses the entire transient response

trace in the time domain for calibration, this method utilizes both leak-induced damping and reflection information. For example, the objective function for the optimization can be expressed as:

$$\max: Z = \frac{C}{1 + \sum\limits_{i=1}^{N}[H_i^m - H_i^p]^2}$$

(68)

where Z is fitness of objective function; H^m is measured pressure head; H^p is predicted pressure head by using numerical models; $i = 1 \dots N$ is time step point for comparison; and C is a constant coefficient. To obtain the potential leak information, different mathematical programming and searching methods have been used for optimizing the objective function of Equation (68), including: genetic algorithm (GA) (Liggett & Chen 1994; Vítkovský *et al.* 2000; Stephens 2008); simulated annealing (SA) (Huang *et al.* 2015); Levenberg–Marquardt (LM) (Kapelan *et al.* 2003), non-linear programming (NLP) (Shamloo & Haghighi 2009, 2010); least squares and match-filter (LSMF) (Al-Khomairi 2008; Keramat *et al.* 2019); Gaussian function (GF) (Sarkamaryan *et al.* 2018); and artificial neural networks (ANN) (Bohorquez *et al.* 2020).

Signal processing-based method (SPM)

In recent years, another type of transient-based method with the aid of different advanced signal processing algorithms, termed as SPM herein, has been developed and used for leak detection in water pipelines. According to the used signal processing methods for transient analysis, the SPM can be divided into several groups as follows:

1. time-frequency analysis based on the empirical mode decomposition (EMD), coupled with Hilbert transform (HT) (e.g., Ghazali *et al.* 2012; Sun *et al.* 2016) or Cepstrum analysis (e.g., Taghvaei *et al.* 2006, 2010; Ghazali *et al.* 2011; Shucksmith *et al.* 2012; Yusop *et al.* 2017);

2. frequency domain variable separation by the matched-field processing (MFP) (e.g., Wang & Ghidaoui 2018a; Wang *et al.* 2019, 2020);

3. statistical analysis through maximum likelihood (ML) (e.g., Wang & Ghidaoui 2018b), or cross-correlation analysis (CCA) (e.g., Beck *et al.* 2005);

4. time domain signal reconstruction based on the least squares deconvolution (LSD) or generalized cross validation (GCV) (e.g., Nguyen *et al.* 2018; Wang & Ghidaoui 2018a; Wang *et al.* 2020).

Despite the fact that these five types of transient-based methods (TRM, TDM, TFRM, ITAM, and SPM) have been developed, validated, and applied for different experimental systems (laboratory or field), it is also observed from various applications in these studies that their effectiveness would be highly dependent on the accuracy of transient models implemented in the method as well as the precision and capacity of transient data measured from the system. Meanwhile, all these methods are mainly limited to relatively simple pipeline systems that may include few series and branched and looped junctions (e.g., Kapelan *et al.* 2003; Duan 2011; Ghazali *et al.* 2012; Shucksmith *et al.* 2012; Duan 2017), while they are unable to deal with pipe systems with complex configurations as commonly seen in practical UWSS. A relevant literature review by Colombo *et al.* (2009) pointed out that the validations and applications of present transient-based leak detection methods are mainly focused on simple systems and many had not yet been involved in field situations. Based on their analysis, one of the main reasons is the potential difficulty in dealing with practical factors/complexities affecting the transient damping and reflections, such as external fluxes, internal junction connections, elbow connections, and other system properties. Moreover, it is also noted that the appropriate combinations of different transient-based methods (and other technologies if possible) will be greatly beneficial to improve the leak detection results for complex UWSS.

Transient-based blockage detection

Partial blockages in aging pipeline infrastructures can be caused by various reasons, including biofilm and deposition (e.g., Figure 1(b)), deformation (Figure 1(d)), corrosion (e.g., Figure 1(e)), and air pocket accumulation (e.g., Figure 1(f)). Partial blockages in pipelines could increase operational costs by reducing the flow capacity as well as increasing the energy dissipation throughout the system (Lee *et al.* 2008a). Unlike leaks, the presence of partial blockages in a pipeline does not result in clear external indicators and

the problem often remains undetected until the pipeline is close to fully constricted. Partial blockages are classified based on their physical extent relative to the total length of the system. Localized constrictions that can be considered as point discontinuities are referred to as discrete partial blockages (Lee 2005). Common examples of this type are partially closed inline valves or orifice plates. In comparison, partial blockages caused by pipe aging are more common and often cover significant stretches of pipe relative to the total pipe length, which are commonly termed as extended partial blockages in this field (Stephens 2008; Duan *et al.* 2012b). Since the diagnosis methods developed for these two types of partial blockages are different in principle, they are presented individually as follows.

Discrete partial blockage detection

Several studies recently dealt with the first type of partial blockage detection – discrete partial blockage in pipelines. The methods used for discrete partial blockage detection can be divided into time-domain and frequency-domain approaches. For the time-domain approach, the principle and procedure are similar to the TRM and ITAM that were developed for leak detection as shown in Figure 10(a), where the location and size of discrete partial blockage can be estimated in the time domain through the analysis of the interaction of waves with partial blockages (e.g., Stephens *et al.* 2004; Stephens *et al.* 2007; Meniconi *et al.* 2011, 2012; Meniconi *et al.* 2016). For the frequency-domain approach, the discrete partial blockage induced transient pattern is firstly derived based on analytical analysis for the 1D transient model, which is then used to inversely determine the potential partial blockage information (location and size) (e.g., Wang *et al.* 2005; Mohapatra *et al.* 2006; Lee *et al.* 2008a; Sattar & Chaudhry 2008; Kim 2018). For example, the FRF result by Lee *et al.* (2008a) is shown as follows:

$$\hat{h}_B = \alpha I_B \cos\left[(2m-1)\pi x_B^*\right] + \beta \tag{69}$$

where $I_B = \Delta H_{B0}/Q_{B0}$ is partial blockage impedance; ΔH_{B0} is steady state head loss across the partial blockage; Q_{B0} is steady state flow across the partial blockage; x_B^* is partial blockage location from the upstream reservoir normalized

by the total pipe length; m is peak number; α and β are constant coefficients. Through different experimental applications (laboratory and field) in the literature, it is shown that these developed transient-based techniques are applicable and accurate for locating and sizing partial blockages in water pipelines, provided that the potential partial blockage to be detected can be approximated as a localized discontinuity in the system.

Extended partial blockage detection

The discussion by Brunone *et al.* (2008) has shown that discrete and extended partial blockages have significantly different impacts on the system responses and the techniques for discrete partial blockages in the literature may not be applicable for extended partial blockages. For the time-domain analysis, the properties of extended partial blockage can be identified through the wave reflections at the ends of partial blockage section (see Figure 15), so that the time-domain method for extended partial blockage detection has been proposed and applied for this purpose (e.g., Tuck *et al.* 2013; Gong *et al.* 2013a, 2014b, 2016; Massari *et al.* 2014, 2015; Zhao *et al.* 2018; Zhang *et al.* 2018; Keramat & Zanganeh 2019). The principle of this time-domain extended partial blockage detection method is similar to the TRM above for the leak detection.

For the frequency-domain analysis, Duan *et al.* (2012c) first developed the transient-based extended partial blockage detection method, which is based on the frequency shift pattern of transient responses that is dependent on partial blockage properties (location, size, and length). This method has been verified with theoretical demonstration and sensitivity analysis as well as validated through laboratory experimental tests (Duan *et al.* 2013, 2014a; Duan 2016). Specifically, the blockage-induced frequency shift

Figure 15 | Illustrative pipeline system with an extended partial blockage.

pattern for a single pipeline system with uniform extended partial blockage can be expressed as follows:

$$\begin{bmatrix} (Y_u + Y_b)(Y_b + Y_d)\cos\left[(\lambda_u + \lambda_b + \lambda_d)\omega_{rfb}\right] \\ +(Y_u - Y_b)(-Y_b - Y_d)\cos\left[(\lambda_u - \lambda_b - \lambda_d)\omega_{rfb}\right] \\ -(Y_u + Y_b)(Y_b - Y_d)\cos\left[(\lambda_u + \lambda_b - \lambda_d)\omega_{rfb}\right] \\ -(Y_u - Y_b)(-Y_b + Y_d)\cos\left[(\lambda_u - \lambda_b + \lambda_d)\omega_{rfb}\right] \end{bmatrix} = 0 \quad (70)$$

where Y is the characteristic impedance of pipeline; λ is wave propagation coefficient; ω_{rfb} = resonant frequencies of the blocked pipe system; the subscripts u, b, d denote pipe sections from upstream to downstream (Figure 15); $R_f = R_{fs} + R_{fu}$ is friction damping factor, with R_{fs} and R_{fu} representing the steady and unsteady friction components, respectively. The detailed expressions have been given previously in this paper.

For better describing the frequency shift pattern induced by the extended partial blockage in the pipeline, Equation (70) can be further simplified as follows (Duan *et al.* 2014a):

$$\Delta\omega^* \approx \frac{2}{\pi}\frac{\varepsilon_A}{2-\varepsilon_A}\left[\sin\left(2\lambda_u\omega_{rf0}\right) - \sin\left(2\lambda_d\omega_{rf0}\right) - \frac{\varepsilon_A}{2-\varepsilon_A}\sin\left(2\varepsilon_L\lambda_0\omega_{rf0}\right)\right] \quad (71)$$

where $\Delta\omega^*$ is the normalized resonant frequency shift induced by the extended partial blockage; ω_{rf0} is the fundamental frequency of intact pipeline system; ϵ_A and ϵ_L are the normalized quantities of blocked area and length in the pipeline. Meanwhile, the mechanism of extended partial blockage-induced frequency shift has been explained in Duan *et al.* (2014a) based on the analytical analysis of 1D wave equation for pipeline with uniform partial blockage. Specifically, their results evidenced that the wave reflection by extended partial blockage can be governed by:

$$R_w = -\left(1 - e^{-i2\pi\frac{\omega}{\omega_b}}\right)\xi_s \quad (72)$$

where R_w is wave reflection coefficient; $\omega_b = 2\pi a_b/2L_b$; a_b and L_b are wave speed and length of partial blockage section (e.g., Figure 15); and ξ_s is the relative change of the characteristic impedance by the partial blockage section along the pipeline. This result reveals clearly the dependence of wave reflection (and thus the transient phase and amplitude changes) on the extended partial blockage properties
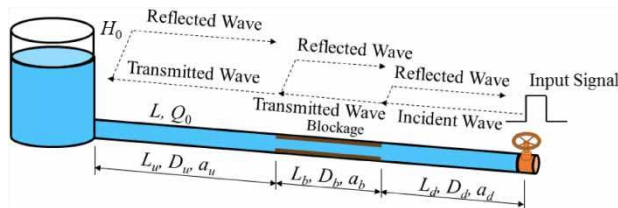
(length and size). For clarification, the changes of transient wave phase and amplitude imposed by an extended partial blockage are shown in Figure 16, with the results normalized by the incident wave quantities.

To enhance the effectiveness of transient-based methods, the coupled time- and frequency-domain method was explored in the study by Meniconi *et al.* (2013), and the application results demonstrated the improvement on the accuracy and efficiency of this type of method for extended partial blockage detection in water pipelines. Meanwhile, this method has also been extended for complex pipe systems by introducing advanced searching technology to solve Equation (70), such as genetic algorithm (GA) (e.g., Datta *et al.* 2018). Nevertheless, this developed transient-based method by Equation (70) or Equation (71) is valid only for uniform partial blockages which have relatively similar severity for each of these blockages (i.e., regular variations), so that the blockage sections can be treated as small uniform pipe sections in these methods. To address this issue, Che *et al.* (2018a, 2019) have investigated the interactions of non-uniform partial blockages with transient waves through analytical derivation and energy analysis. The results indicated the non-uniform partial blockage may induce very different modification patterns on both frequency shift and amplitude change of transient waves from the uniform case. To be specific, the resonant frequency shifts induced by non-uniform partial blockages become less evident for higher harmonics of transient waves. The mechanism understanding and derived results from these studies are useful to the application and improvement of current transient-based methods for extended partial blockage detection in UWSS.
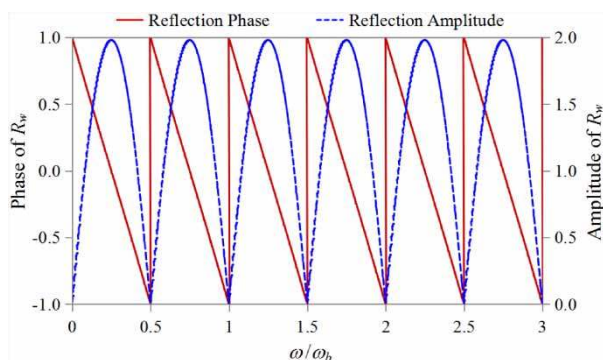
Furthermore, the extended partial blockage detection method has also been further developed by advanced mathematical analysis and signal processing techniques for more realistic situations such as rough partial blockages with irregularity. For example, based on the multiple-scale wave perturbation analysis, the effect of wave scattering by rough partial blockages was derived and applied in Duan *et al.* (2011b, 2014b, 2017b). Meanwhile, Jing *et al.* (2018), Blåsten *et al.* (2019), and Zouari *et al.* (2019) have developed the pipe area reconstruction methods for rough partial blockage detection in both single and branched pipeline systems based on mathematical transformation and linear approximation (e.g., Liouville transformation and impulse response function), followed by laboratory experimental validations under different partial blockage conditions in Zouari *et al.* (2020). These studies have provided the possibility of extending current transient-based method to practical pipeline systems.

Transient-based pipe branch detection

In addition to the two common defects mentioned above (leakage and partial blockage), unknown branch is another important issue that is usually encountered in complex UWSS, such as illegal connections and non-recorded branches (e.g., Figure 1(c)). Identifying these unknown branches becomes important to the construction, operation, monitoring, and maintenance of UWSS. Unfortunately, these unknown branches commonly exist underground in UWSS and are not easy to detect with current commercial tools. For this purpose, transient-based method has become a good choice to solve this problem. In this regard, Duan & Lee (2016) first developed the transient-based method for dead-end branch detection (e.g., branch section [3] in Figure 14). In that study, the frequency domain shift pattern has been derived for the dead-end branched pipe system, which can be inversely used for identifying the properties of potential branches (connecting location, size, and length) with the aid of a GA-based optimization procedure. Thereafter, Meniconi *et al.* (2018) proposed a time-domain method using the wave reflections for branch detection based on a wavelet analysis technique. Their results have been validated through a field test, indicating the acceptable accuracy of branch detection results.

Figure 16 | Changes of transient wave phase and amplitude induced by extended partial blockage.

Currently, however, all these methods are developed and applicable only for simple pipeline systems that include very few and simple branches with known intact system configurations.

Recently, an inverse transient analysis method based on the ANN framework was developed by Bohorquez *et al.* (2020) for a comprehensive diagnosis of pipe leakage and system topology (which may include unknown branches). However, this method requires abundant prior-known data information for ANN training as well as relatively high computation capacity, which is therefore not feasible or practical for complex UWSS at current stage. Based on these preliminary studies, transient-based method has been shown to be a promising approach for pipe branch characterization and detection, but still needs further development and improvement for its applicability range and accuracy in the future.

Transient-based multi-defect detection

In practical UWSS, the potential problems of different pipe defects and system operations may occur simultaneously in the system (which is actually very common in UWSS), so that the types and numbers of defects are usually not known in advance. As a result, the application of the above-mentioned transient-based defect detection (TBDD) methods becomes difficult or even invalid. To this end, preliminary studies in the literature have made efforts on developing more holistic TBDD in order to achieve the capability of multiple-defect detection in pipelines. For instance, Stephens *et al.* (2004) have successfully applied the inverse transient wave analysis for locating the leakage, air-pocket, and discrete partial blockage in two field test pipeline systems. Thereafter, Sun *et al.* (2016) developed a time-frequency analysis method based on EMD-HT algorithm, which can be applied to identify different types of defects including leakage, discrete and extended partial blockages, and branched junction. The proposed method and application procedure have been validated through laboratory experimental tests. The results demonstrated that this method could provide good detection accuracy for the types, numbers, and locations of multiple defects, but failed to quantify the sizes of all the defects in the system. Meanwhile, Kim (2016) proposed the transient impedance method for the detection of leakage and partial blockage

in a branched pipeline system, followed by the recent studies for the multiple partial blockage detection in a single pipeline (Kim 2018) and multiple leaks detection in pipe networks (Kim 2020).

Recently, Duan (2020) developed a TFRM for the simultaneous detection of leakage and partial blockage in the pipeline. The TMA method was applied to derive the analytical results of FRF in a simple pipeline system with both leakage and discrete partial blockage. The results implied that the leak-induced and partial blockage-induced patterns could be treated approximately to be independent (i.e., linear superposition), as long as the impedance factors of these two defects are much smaller than 1 (so that their product is also much smaller than 1). This finding from that study has been validated through both different numerical and experimental applications.

The development progress and achievement of these TBDD methods have given the promise and confirmation on the feasibility and possibility of this type of innovative method for pipeline system diagnosis under different conditions, although it also indicates a relatively long distance to make further advances in this field in the future.

ADVANCES FOR TRANSIENT RESEARCH AND RECOMMENDATIONS FOR FUTURE WORK

Despite the substantial progress and achievement made in the past many years, the developed model and methods still could not cover all the possible situations in practical UWSS. That is, the high complexities in the realistic UWSS may cause the failure or inaccuracy of these models and methods, especially when the transients are utilized more and more for system diagnosis and management rather than for the transient system design purposes only (e.g., system strength and protection devices). Meanwhile, transient flows are common states of UWSS (as common as steady flow states), which may be triggered at any time and anywhere in the system due to various factors including both regular/normal and unexpected operations of the system, such as (but not limited to) demand variation, valve operation, pipe burst, pump switching and power failure, system construction and maintenance, etc.). In this connection, understanding the very details of transient

evolutions in the system becomes important to the system operation and management, which may present relatively high requirements for transient models and methods.

To address these issues and make further advances on the transient research, many researchers and engineers in this field have been involved in different advanced topics on transient modeling and utilization. Through the literature review, some important transient research topics and directions that have been initiated by the researchers in this field can be briefly summarized as follows:

1. multi-phase transient flows, including transient air–water interaction and air-pocket analysis in the UWSS (e.g., Wylie *et al.* 1993; Zhou *et al.* 2002, 2011, 2018; Zhu *et al.* 2018; Alexander *et al.* 2019, 2020);
2. high-frequency and radial waves in both actively and passively generated transients for system diagnosis (e.g., Mitra & Rouleau 1985; Che & Duan 2016; Louati & Ghidaoui 2017a, 2017b, 2019; Che *et al.* 2018b);
3. transient generation (bandwidth and amplitude) for the application of transient-based methods (e.g., Brunone *et al.* 2008; Lee *et al.* 2008b, 2015, 2017; Haghighi & Shamloo 2011; Meniconi *et al.* 2011);
4. transient noise and uncertainty analysis for transient modeling and utilization (e.g., Duan *et al.* 2010d, 2010e; Dubey *et al.* 2019; Duan 2015, 2016);
5. transient-based skeletonization and design for complex UWSS (e.g., Huang *et al.* 2017a, 2017b, 2019, 2020a, 2020b);
6. transient data measurement and transfer (e.g., Brunone *et al.* 2000; Brunone & Berni 2010; Kashima *et al.* 2012, 2013; Brito *et al.* 2014; Leontidis *et al.* 2018).

In addition, with the rapid development of computational capacity, the efficient multi-dimensional simulations (e.g., CFD-based 2D or 3D modeling) will become gradually feasible for both fundamental research and small-scale application purposes (e.g., Martins *et al.* 2014, 2016, 2018; Che *et al.* 2018b). With these advanced research methods and simulation tools, it is expected that the understanding of transient-related phenomena and the application of transient-based methods would be greatly enhanced and thereby effectively utilized for the development and management of smart UWSS.

CONCLUDING REMARKS

This paper presents a state-of-the-art review on the progress and accomplishment in the field of transient research and application in the urban water supply system (UWSS), with providing perspectives for comprehensive understanding and essential dissemination on the necessity and significance of transient research for UWSS.

On one hand, the transient theory and models developed in the literature are revisited in a systematic way for the transient simulations and analysis in UWSS, including the derivations of governing equations in 1D and 2D forms, unsteady friction and turbulence formulas and viscoelastic models. Meanwhile, the common numerical methods for solving the transient models in both time and frequency domains are introduced, such as the MOC and the TMA. In particular, typical examples are given in the paper for demonstrating the applications of these models and methods. On the other hand, the utilizations of transient flows for pipeline diagnosis, termed as TBDD method, are reviewed for different types of pipe defects with introducing the main principles and application procedures. In particular, four types of common pipe defects in UWSS are illustrated herein – leakage, discrete partial blockage, extended partial blockage, and unknown branch. The advantages and limitations of each developed TBDD method have been elaborated through example demonstrations and/or explanatory analysis.

Based on the literature review, the potential advances and implications as well as recommendations for the future work on transient research are also discussed in the paper, with the aim to better assist in the development and management of smart UWSS. Finally, despite the fact that a total of over 200 publications have been reviewed and analyzed in this paper, it is very possible that other relevant publications might have been omitted unintentionally during preparation of the current paper.

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DATA AVAILABILITY STATEMENT

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

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