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Research papers

The influence of non-uniform blockages on transient wave behavior and blockage detection in pressurized water pipelines

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ABSTRACT

Blockages in piping systems are formed from potentially complex combinations of bio-film build up, corrosion by-products, and sediment deposition. Transient-based methods seek to detect blockages by analyzing the evolution of small amplitude pressure waves. In theory, such methods can be efficient, nearly non-intrusive and economical but, thus far, studies have only considered symmetrical blockages, uniform in both the radial and longitudinal directions. Laboratory experiments are described here that involve pipe blockages with various levels of irregularity and severity; the way the transient response is affected by a non-uniform blockage is investigated. The differences between uniform and non-uniform blockages are quantified in terms of the rate that wave envelopes attenuate and the degree that phases are shifted. Two different methods for modeling these impacts are compared, namely through an increase in pipe roughness and through a wave scattering model. Wave scattering is shown to play a dominant role in explaining both wave envelope attenuation and phase shift. The accuracy of existing transient-based methods of blockage detection in the frequency domain is also examined, and is found that the predictions of rough blockage locations and sizes by current method are in good agreement with data, with relatively larger discrepancies for rough blockage lengths.

1. Introduction

Constrictions in pipe cross-sectional area, in the form of partial blockages, can form naturally on pipe walls and can gain significant lengths in water pipelines (see Fig. 1). In water supply pipes, drainage pipes, crude oil pipes, and arterial line systems, many factors can lead to the generation of these blockages including bio-film build up, corrosion, and sediment deposition. These blockages can cause additional energy loss and thus either an increase in pumping costs or a reduction in performance. Under unsteady flows, blockages often modify the pressure response and affect the effectiveness of surge mitigation devices. Duan et al. (2011a) show that transient wave scattering in pipes due to irregular and non-uniform blockages may cause attenuation of the wave envelope and shifts in the wave phase. These shifts are caused by a temporal and spatial redistribution of energy, not a dissipation of energy.

The study of transient pressure responses and its deviation from the expected response provide a means of condition diagnosis and numerous transient-based methods have been developed for detecting leaks and blockages in pipeline systems (Brunone, 1999; Ferrante and Brunone, 2003; Wang et al., 2002, 2005; Covas et al., 2005; Mohapatra et al., 2006; Lee et al., 2006, 2008, 2013; Sattar et al., 2008; Stephens, 2008; Meniconi et al., 2011, 2013; Duan et al., 2011b, 2012, 2013, 2014). The methods typically inject a customized pressure wave into the pipeline and fault properties are determined from the temporal or spectral analyses of the measured responses at different locations (Lee et al., 2013). In these applications, since the detailed geometry of the pipe blockages is initially unknown, pipe blockages are approximated either as uniform constrictions in the radial and longitudinal direction or inner wall roughness represented by different friction factors (Brunone et al., 2008; Stephens, 2008; Ebacher et al., 2011; Duan et al., 2012, 2013, 2014; Meniconi et al., 2011, 2012, 2013). These simplifications neglect the complex interaction of blockage irregularities and non-uniformities, and thus false adjustments of friction factors, wave speeds, and material properties often substitute for real pipe states (McInnis and Karney, 1995; Ebacher et al., 2011; Stephens et al., 2013; Duan et al., 2010a, 2013). It is noted that these adjustments are non-physically based and their necessity highlights the fact key behaviors

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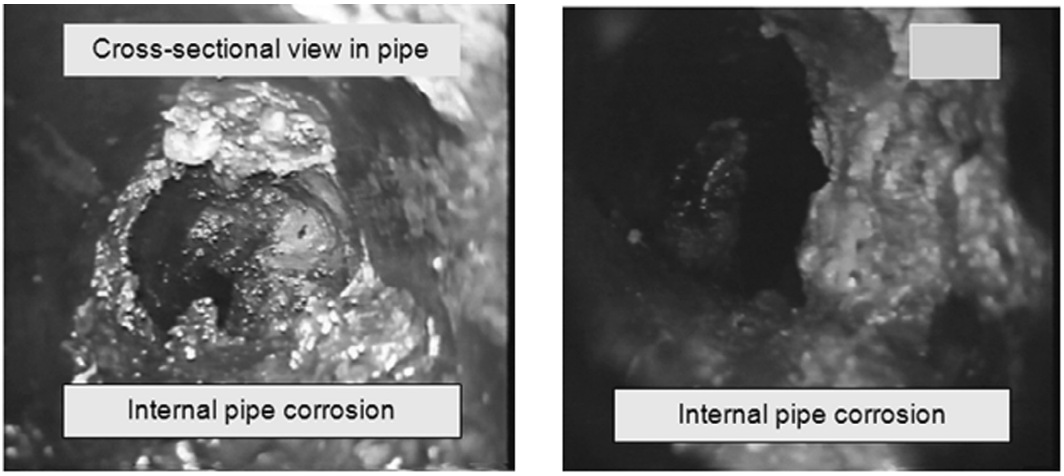

Fig. 1. Variation of pipe inner diameters observed in an aged urban water supply main. adapted from Stephens (2008)

are not modelled accurately within these models.

Despite numerous published works on blockage detection, experimental studies have not yet tested blockages of irregular geometries and little is known regarding the way non-uniform blockages alter the transient response. Can non-uniform blockages be usefully represented as uniform pipe constrictions or pipes of large roughness? Are wave scattering effects due to the blockage irregularities important? In this paper, numerical and experimental tests are conducted for blockages of different geometries to achieve three specific ends: (1) to identify the changes that blockage non-uniformity impose on the transient response; (2) to compare the accuracy of different modeling approaches for the non-uniform blockage; and (3) to examine the accuracy of current blockage detection method when applied to a non-uniform blockage. The aim of the study is to improve the modeling and detection approaches for the non-uniform blockages.

2. Models and methods

2.1. Numerical model and simulation scheme

In this study, the 1D continuity and momentum equations of unsteady pipe flows are used for the numerical simulations, with following expressions (Wylie et al., 1993; Ghidaoui et al., 2005; Duan et al., 2011a),

$$\frac{\partial(\rho A)}{\partial t}+\frac{\partial(\rho Q)}{\partial x}=0, \tag{1}$$

$$\frac{\partial(\rho Q)}{\partial t}+A\frac{\partial P}{\partial x}+\pi D\tau_w=0, \tag{2}$$

where ρ = fluid density; $A = A(x)$ = pipe cross-sectional area; $D = D(x)$ = pipe internal diameter; $Q = Q(x, t)$ = pipe discharge; $P = P(x, t)$ = pressure; x = spatial coordinate; and t = temporal coordinate; $\tau_w = \tau_w(x, t)$ = wall shear stress. To represent the damping effect of rough pipe blockages, the Colebrook–White equation based Darcy friction factor (Wylie et al., 1993) and the unsteady friction model for rough pipe flows in Vardy and Brown (2004) are used to describe the wall shear stress as follows:

$$\tau_w=\frac{\rho f|Q|Q}{8A^2}+\frac{4\nu\rho}{AD}\int_0^t\frac{\alpha e^{-\beta(t-t')}}{\sqrt{\pi(t-t')}}\frac{\partial Q}{\partial t}dt' \tag{3}$$

where f = friction factor based on the Colebrook–White equation; ν = kinematic viscosity of fluid; t' = a dummy variable representing the instantaneous time in the time history; α, β = coefficient, and

(i) for turbulent smooth pipe flows,

$$\alpha=\frac{D}{4\sqrt{\nu}}\quad\text{and}\quad\beta=\frac{0.54\nu}{D^2}\boldsymbol{Re}_0^{\log(14.3/\boldsymbol{Re}_0^{0.05})}, \tag{4a}$$

(i) for turbulent rough pipe flows,

$$\alpha=0.00913\left(\frac{\varepsilon}{D}\right)^{0.39}\sqrt{\frac{D^2}{\nu}\boldsymbol{Re}_0}\quad\text{and}\quad\beta=1.408\left(\frac{\varepsilon}{D}\right)^{0.41}\frac{\nu}{D^2}\boldsymbol{Re}_0, \tag{4b}$$

in which, ε = pipe wall roughness; $\mathbf{Re}_0$ = initial Reynolds number.

To obtain the numerical results (e.g., pressure head), the method of characteristics (MOC) with a 2nd-order discretization accuracy scheme, which has been well developed in previous studies of the authors (e.g., Duan, 2011c; Ghidaoui et al., 2005), is used to solve above models for the experimental pipeline system established later in this paper.

2.2. Theoretical model of wave scattering by rough blockage

In addition to friction damping, the non-uniform blockage scatters waves. The wave scattering attenuates the main signal as shown in Duan et al. (2011a) in which an analytical relationship between the incident waves and the non-uniformity of the blockage is derived. Duan et al. (2011a) show that the wave scattering causes the energy to be spread over multiple waves and is distinct from frictional dissipation effects. The wave envelope was found to be reasonably modelled through an exponential decay function:

$$B=B_0e^{-\lambda x}=B_0e^{-a\lambda t}, \tag{5}$$

where $B = B(x)$ = amplitude of wave envelope with distance along the pipeline or with the equivalent time $t = x/a$ with a = wave speed; B_0 = amplitude of the incident wave; $\lambda = \lambda_r - i\lambda_i$, i = imaginary unit, and λ_r and λ_i = wave damping factor and wave phase change (frequency shift) factor, respectively, such that:

$$\lambda_r=\frac{\alpha k^2\delta_A^2}{\alpha^2+4k^2},\quad\text{and}\quad\lambda_i=\frac{k\alpha^2\delta_A^2}{2(\alpha^2+4k^2)}, \tag{6}$$

in which δ_A = coefficient of variation (COV) of the pipe cross-sectional area in the spatial domain which quantifies the irregularity of the blockage severity and $\delta_A = \sigma_A/\mu_A$ with σ_A and μ_A being the standard deviation and mean values of the pipe area; k = incident wave number and $k = \omega/a$, with ω = wave frequency; α = spatial correlation coefficient of the blockage and $\alpha \sim 1/L_c$ with L_c = correlation length which describes the spatial variability of the blockage. The neglect of pipe friction effect in these expressions allows the relative importance of wave scattering to be compared to pipe friction later in this study. The