Journal of Civil Engineering and Urbanism

Volume 4, Issue 3: 282-286 (2014) ISSN-2252-0430

Comparative Hydraulic Simulation of Water Hammer in Transition Pipe Line Systems with Different Diameter and Types

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ABSTRACT: The transient pressure caused by water hammer events is sufficient to fracture pipes and some equipment, and for this reason alone the study of the phenomenon in transitional pipe line system is of considerable practical importance. In addition, the diameter and pipe type should be considered to attenuate the transient pressure wave. The paper describes the theory about transient analysis and shows technique in numerical simulation of water hammer in transitional pipe line systems by substituting for different pipe types and diameter or both simultaneously and analyzing the velocity and the type of direct or reflected transitional waves which will the intensities in places where these changes occur and also in boundary conditions. The results indicated that pipe selection and substitution could be from low elastic modulus to high elastic modulus. In order to reduce pressure fluctuation it is advisable to choose pipes with most similar elastic modulus and one greater diameter size.

Keywords: Elastic modulus, Pipe line, Transient pressure, Water hammer

ORIGINAL ARTICLE
Received 26 Apr. 2014
Accepted 20 May. 2014

INTRODUCTION

Thus the growth of knowledge of the physical aspect of reality cannot be regarded as a cumulative process. They speak of the laws of nature, for example, which are simply models that explain their experience of reality at a certain time. Later generations of scientists typically discover that these conceptions of reality embodied certain implicit assumptions and hypotheses that later on turned out to be incorrect. Unsteady fluid flows have been studied since man first bent water to his will. The ancients understood and applied fluid flow principles within the context of traditional, culture-based technologies. With the arrival of the scientific age and the mathematical developments embodied in Newton's Principia, our understanding of fluid flow took a quantum leap in terms of its theoretical abstraction (Vanderburg 1986).

The impetus for a shift from the traditional deterministic approach to a stochastic model of transient analysis is three-fold. First, a need exists for adequate hydraulic performance assessment; transient performance should be comprehensibly evaluated on the basis of the spectrum of pressures that systems experience. Beyond just knowing the extreme values of transient pressures, an estimate of the likelihood of their occurrence would be enormously useful; as stated in the European Union design guideline proposal, a high value of modeled hydraulic pressure load with a low frequency of occurrence would lead to the same failure rate (and the same contribution to the limit states of the pipe structure) as a moderate modeled hydraulic load exerted at high frequency (Pothot and Lemmens 2001). The core material discussed in this paper has been collectively reported in various venues (Wylie et al., 1993). but has not been hitherto organized in a systematic fashion or appeared in English; particularly the Monte Carlo simulation and comparison with the results from analytical probabilistic model have never been previously published by any journal. The International Symposium on Stochastic Hydraulics has been organized on a four year basis since 1972, and the earlier focus and achievement in hydrologic frequency analysis then expanded rapidly to a wider horizon of hydraulic engineering. Because of the uncertainties on the shape, size, and mechanic properties of sediment and the stochastic nature of the flow in rivers (Buhman et al., 2002), a large amount of theoretical and experimental research works are making progress on the complicated and highly stochastic processes of sediment incipient, sediment transport, and channel morphology (Nino and Garcia 1986; Paintal, 1971).

Mays, Tung, and other researchers have made great contributions to the uncertainty and reliability analysis, risk-based optimal planning/design of municipal water supply, and distribution systems; and also the statistical modeling and risk-based optimal design of sewer systems .Particularly, a recently published work. Focuses on the probabilistic analysis of transient design for water supply systems (Revell and Ridolfi, 2002).

MATERIAL AND METHODS

Although hydroelectric generation accounts for a much smaller proportion of energy production today, the problems associated with controlling the flow of water through penstocks and turbines remains an important application of transient analysis.

Mass and Momentum Equations for One-Dimensional Water Hammer Flows

Hydrogenation companies contributed heavily to the development of fluids and turbo machinery laboratories that studied, among other things, the phenomenon of water hammer and its control. Hydraulic transients are critical design factors in a large number of fluid systems from automotive fuel injection to water supply, transmission, and distribution systems. Today, long pipelines transporting fluids over great distances have become commonplace, and the almost universal development of sprawling systems of small pipe diameter, high-velocity water distribution systems has increased the importance of wall friction and energy losses, leading to the inclusion of friction in the governing equations. Michaud is generally accorded that distinction. Michaud (1878) examined the use of air chambers and safety valves for controlling water hammer. Near the turn of the nineteenth century, researchers like Weston (1885), Carpenter (1893) and Frizell (1898) attempted to develop expressions relating pressure and velocity changes in a pipe. Frizell was successful in this endeavor and he also discussed the effects of branch lines, and reflected and successive waves on turbine speed regulation. Similar work by his contemporaries Joukowsky (1898) and Allievi (1903) however, attracted greater attention. Joukowsky produced the best known equation in transient flow theory, so well-known that it is often called the ‘‘fundamental equation of water hammer.’’ He also studied wave reflections from an open branch, the use of air chambers and surge tanks, and spring type safety valves. Joukowsky’s fundamental equation of water hammer is as follows:

$$\Delta P = \pm \rho . A . \Delta V \ or \ \Delta H = \pm \frac{a.\Delta V}{g} \qquad (1)$$

Where a= acoustic (water hammer) wave speed, $P = \rho . g\ (H - Z)$= piezometric pressure, Z=elevation of the pipe centerline from a given datum, H= piezometric head, ρ= fluid density, u=local longitudinal velocity, A=cross-sectional area of the pipe and g= gravitational acceleration. The positive sign in Eq (1) is applicable for a water-hammer wave moving downstream while the negative sign is applicable for a water-hammer wave moving upstream. Readers familiar with the gas dynamics literature will note that $\Delta p = \mp \rho . A . \Delta V$is obtainable from the momentum jump condition under the special case where the flow velocity is negligible in comparison to the wave speed. The jump conditions are a statement of the conservation laws across a jump (shock) (Jaeger1933). These conditions are obtained either by directly applying the conservation laws for a control volume across the jump or by using the weak formulation of the conservation laws in differential form at the jump. Further refinements to the governing equations of water hammer appeared in Jaeger (1956), Wood (1944), Rich (1951), Parmakian (1963), Streeter and Wylie (1967). Their combined efforts have resulted in the following classical mass and momentum equations for one-dimensional (1D) water-hammer flows:

$$\frac{a^2}{g} . \frac{\partial v}{\partial x} + \frac{\partial H}{\partial t} = 0 \qquad (2)$$

$$\frac{\partial v}{\partial t} + g \frac{\partial H}{\partial t} + \frac{4}{\rho . D} \tau_w = 0 \qquad (3)$$

In whichτ_w= shear stress at the pipe wall, D= pipe diameter, X=the spatial coordinate along the pipeline, and t= temporal coordinate.

Discussion of the 1D Water Hammer Mass and Momentum Equations

Limitations of these equations: Rapid flow disturbances, planned or accidental, induce spatial and temporal changes in the velocity (flow rate) and pressure (piezometric) Head) fields in pipe systems. Such transient flows are essentially unidirectional (i.e., axial) since the axial fluxes of mass, momentum, and energy are far greater than their radial counterparts. The research of Mitra and Rouleau (1985) for the laminar water hammer case and of Vardy and Hwang for turbulent water-hammer supports the validity of the unidirectional approach when studying water-hammer problems in pipe systems. A more detailed derivation can be found in Chaudhry (1987). Using the Reynolds transport theorem, the mass conservation (‘‘continuity equation’’) for a control volume is as follows (Zhang et al 2003).

$$\frac{\partial}{\partial t} \int_{cv} \rho . dv + \int_{cs} \rho (v.n) dA = 0 \qquad (4)$$

Where CV = control volume, CS =control surface, n =unit outward normal vector to control surface, **v** = velocity vector Referring to Fig. 1, Eq. (4) yields:

$$\frac{\partial}{\partial t} \int_{x}^{x+\delta x} \rho A dx + \int_{cs} \rho (v.n) dA = 0 \qquad (5)$$

The local form of Eq. (5) obtained by taking the limit as the length of the control volume shrinks to zero.

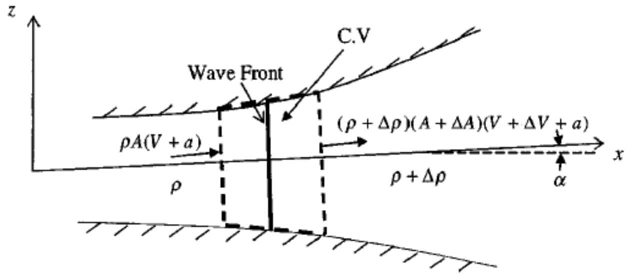

Figure 1. Control volume diagram used for continuity equation derivation

Then:

$$\frac{\partial(\rho.A)}{\partial t} + \frac{\partial(\rho.A.V)}{\partial x} = 0 \qquad (6)$$

Equation (6) provides the conservative form of the area-averaged mass balance equation for 1D unsteady and compressible fluids in a flexible pipe. The first and second terms on the left-hand side of Eq. (6) represent the local change of mass with time due to the combined effects of fluid compressibility and pipe elasticity and the instantaneous mass flux, respectively. Equation (6) can be rewritten as follows:

$$\frac{1}{\rho}\frac{D_\rho}{D_t} + \frac{1}{A}\frac{DA}{Dt} + \frac{\partial V}{\partial x} = 0 \ or \ \frac{1}{\rho A}\frac{A.D_\rho}{D_t} + \frac{\partial v}{\partial x} = 0 \qquad (7)$$

Where $\frac{D}{D_t} = \frac{\partial}{\partial t} + V\frac{\partial}{\partial x}$ = substantial (material) derivative in one spatial dimension. Realizing that the density and pipe area vary with pressure and using the chain rule reduces Eq.(7) to the following:

$$\frac{1}{\rho}\frac{d_\rho}{d_t}\frac{DP}{Dt} + \frac{1}{A}\frac{dA}{dt}\frac{DP}{Dt} + \frac{\partial V}{\partial x} = 0 \ or \ \frac{1}{\rho a^2}\frac{D_\rho}{D_t} + \frac{\partial v}{\partial x} = 0 \qquad (8)$$

The momentum equation for a control volume is:

$$\sum F_{ext} = \frac{\partial}{\partial t}\int_{cv} \rho, vV + \int_{cs} \rho \vartheta (v.n) dA \qquad (9)$$

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Applying Eq. (9) to the control volume of Fig. 2; considering gravitational, wall shear and pressure gradient forces as externally applied; and taking the limit as δxtends to zero gives the following local form of the axial momentum equation:

$$\frac{\partial \rho AV}{\partial t} + \frac{\partial \beta \rho A v^2}{\partial x} = -A\frac{\partial P}{\partial x} - \pi D \tau_w - \gamma A sin\alpha \qquad (10)$$

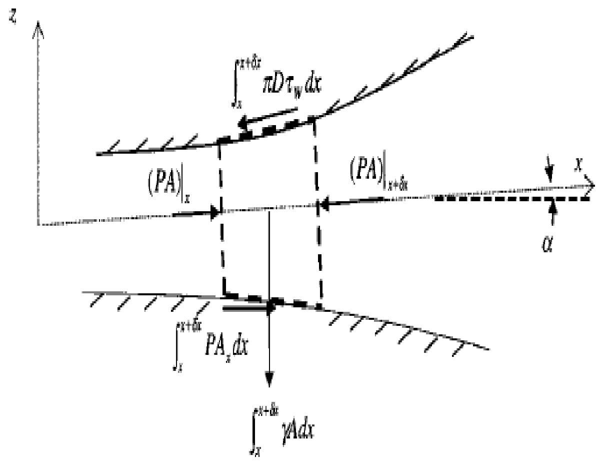

Figure 2. Control volume diagram used for momentum equation derivation

RESULTS AND DISCUSSION

In the table (1) Xin is the beginning of the pipeline, Xf is the end of pipeline, Zi is height of pipeline starting point, Zf is height of the ending point of pipeline and %p is slope of the pipeline. To accomplish this, we should simulate the transmission pipeline specifications.

By considering how the fluid velocity causes water hammer, changes in the rate of velocity in transmission lines get so important. By regarding this equation (Mesbahi 2009):

$$\Delta P = \frac{\alpha \times \Delta H}{g} \qquad (11)$$

If the velocity changes intensity increase, pressure variation will go up. Actually diameter and pipe type role is Undeniable in water hammer phenomenon. As a baseline for comparing other we choose cast iron pipe with these specification: diameter is 600 mm and velocity is 1.72 m/s then we change diameter and pipe type simultaneously in X=4000m and analyze these replacements in pipeline and pump station (critical point of pipeline).

By assuming:

1. Replacing the cast iron pipe to Polyethylene with different diameters
2. Replacing Polyethylene to cast iron pipe with different diameters

In fact, we consider hard and soft material.

Now in x=4000 we consider these options and alternatives:

1. Replace pipe from DCI600 TO PE 600 type but diameter remains constant
2. Change pipe type and choose one size smaller diameter (DCI600 TO PE 496/6)
3. Change pipe type and choose one size greater diameter (DCI600 TO PE 709/4)

Thus we draw graph related to the pressure against position and also in x=4000 m we draw pressure against time graph.

In part 2 as a baseline to compare other we model Polyethylene pipe with diameter of 600mm.

1. Pipe type change but diameter remains constant DCI600 TO PE 600
2. Pipe type change and choose one size smaller diameter DCI600 to PE 496/6
3. Pipe type change and choose one size greater diameter DCI600 to PE 709/4.

Table 1: Technical specifications for water transmission pipelines that is used in this research(Hasanzade 2013)

Pipe	L(m)	D(m)	Xi(m)	Zi(m)	Xf(m)	Zf(m)	%P
1	50	0.6	0	3	3.6875	3.6875	1.375
2	3950	0.6	50	3.6875	58	58	1.375
3	1576	0.6	4000	58	119	119	3.87

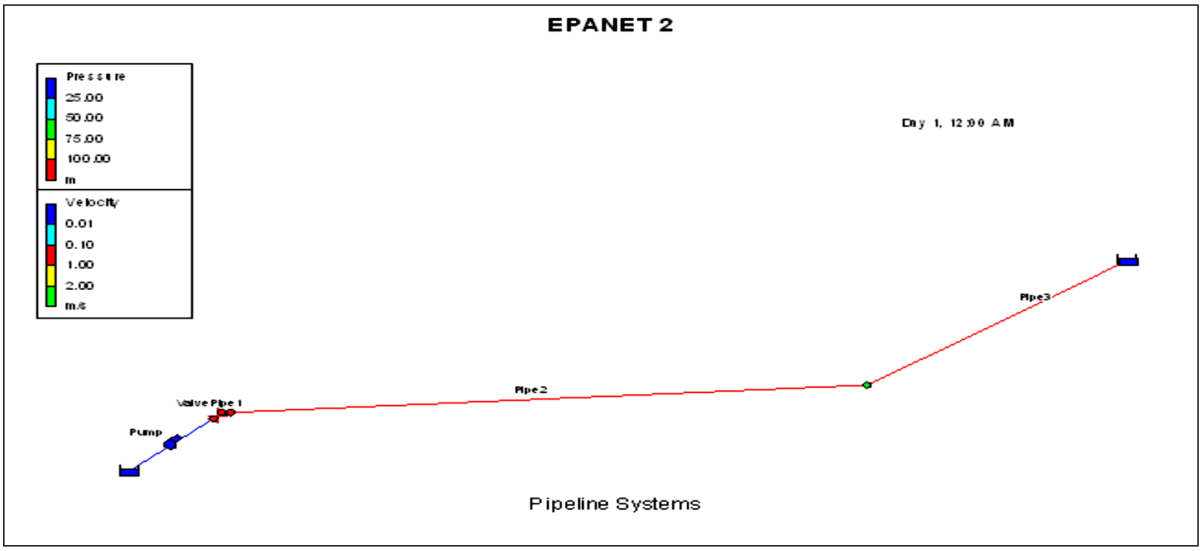

Figure 3. Pipe streamline in EPANET software

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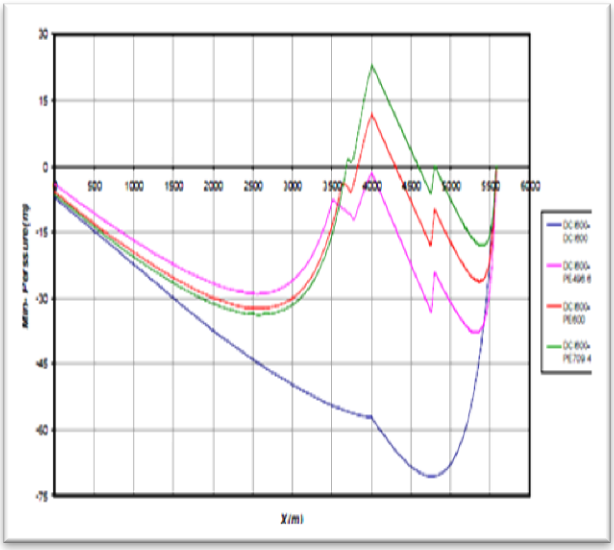

Figure 4. Minimum pressure variation against location

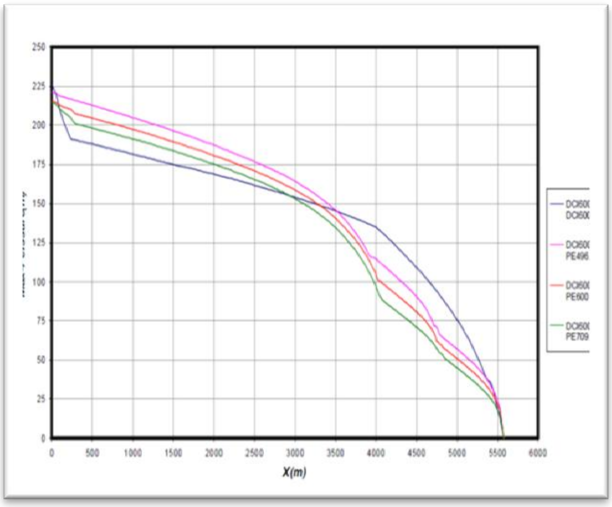

Figure 5. Maximum pressure variation against location

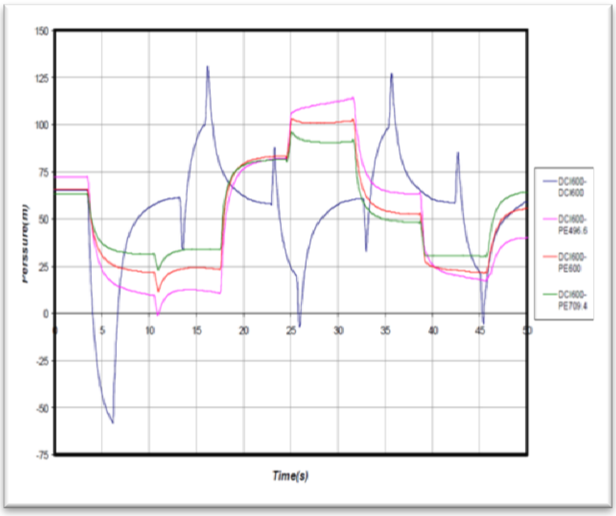

Figure 6. Pressure variation against time

Replacing the cast iron pipe to Polyethylene with different diameters

A. Maximum and minimum pressure decrease when diameter size increases.

B. Max pressure inclines before the location of replacement, increasing diameter size cause lower pressure inclining.

C. Min pressure decline before the location of replacement so by increasing diameter we got lower pressure declining.

D. At pump station by increasing diameter of Polyethylene pipe, maximum and minimum pressure also decrease but max pressure decrease from smaller diameter to greater diameter and min pressure decline from greater diameter to smaller one.

E. Water pressure interval decline by changing pipe type and inclining diameter.

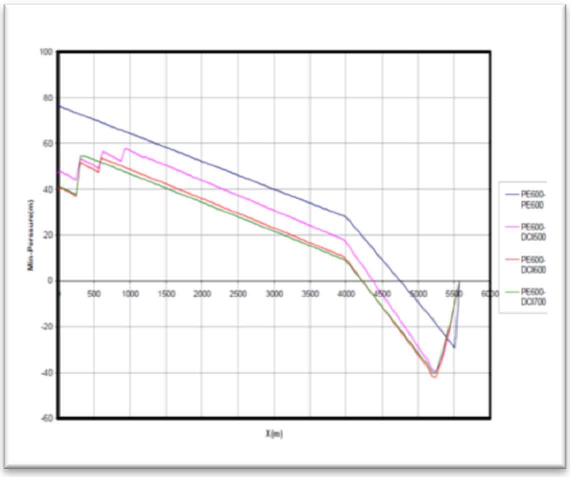

Figure 7. Minimum pressure variation against position

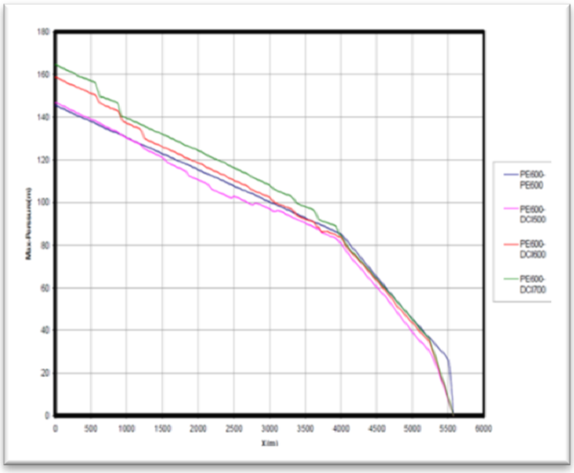

Figure 8. Maximum pressure variation against position

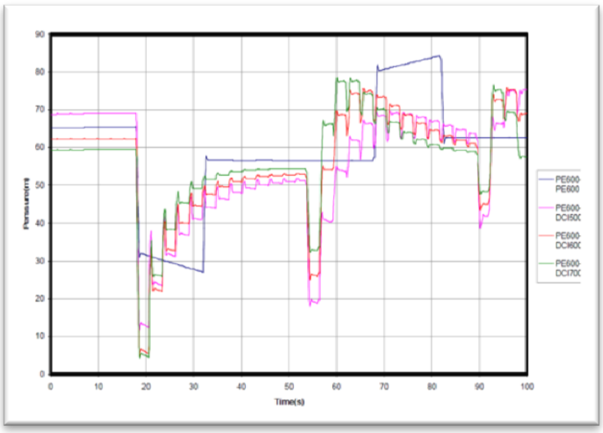

Figure 9. Pressure variation against time

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Replacing Polyethylene to cast iron pipe with different diameters

3. Increasing diameter size caused more pressure (Pressure increase in DCI 600 is greater than DCI 700).

B. Min pressure decline during the transmission line so increasing diameter brings about greater pressure incline (there in an exception between 320 and 600 distance).

C. At pump station by increasing diameter, max pressure also increase but minimum pressure decrease from smaller diameter to greater diameter.

D. pressure changing interval reduces.

According to the above results, in designing transmission pipelines if diameter or pipe type replacement or both inevitable due to economical and technical reasons it is better to check the effect of these substitutions carefully.

Now results for controlling water hammer

1. It is better to avoid diameter or pipe type replacement because it causes turbulence in max and min pressure of the system.

2. By reducing diameter from DCI 600 to DCI 500, in the beginning of pipeline, min and max pressure Respectively decrease 78% and 3% and in x=4000 min pressure raise up to 34% and max pressure up to 3%. By increasing diameter from DCI 600 to DCI 700, in the beginning of pipeline, min and max pressure.

Respectively decrease11% and 3% and in x=4000 min pressure decline 32% and max pressure incline 0.5%. In fact, by choosing one size greater or smaller diameter water hammer intensity remains constant due to safety factor of equipments so this replacement do not recommend.

3. By changing pipe gender from DCI 600 to PE 600, in the beginning of pipeline, min and max pressure Respectively decrease 17% and 4% and in x=4000 min pressure decline 12% and max pressure raises up to 22%. By changing from DCI 600 to PE 700, in the beginning of pipeline, min and max pressure, respective decrease11% and 3% and in x=4000 min pressure decline 32% and max pressure inclines 0.5%.

The results indicate that pipe selection and substitution should be from low elastic modulus to high elastic modulus. In order to reduce pressure fluctuation, it is advisable to choose pipes with most similar elastic modulus In order to reduce pressure fluctuation.

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