Introducing a New Computer Code, H-Hammer, to Solve Fluid Transients in Pipe Flow

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Abstract

Sudden change of flow conditions in a pipeline may cause the flow to become time dependent and would start an undesirable physical phenomenon called water hammer. These sudden changes can be caused by variety of scenarios and some of them include valve operations (opening or closing), sudden power loss at pump stations and load rejections or load acceptance at the turbines, etc. Because of its very costly and sometimes deadly consequences, it is quite important that transient scenarios be considered for pipe systems at design stage to ensure safety and longevity of them. The present study is an attempt to develop a comprehensive computer software that is capable of simulating, analyzing and solving most commonly encountered fluid transient events. The code developed, titled as H-Hammer, is already capable of using many boundary conditions to tackle a large variety of problems involving fluid transients. Within the code, the Method of Characteristics (MoC) are used to solve the basic unsteady pipe flow equations. The code utilizes AutoCAD, Visual Basic 6.0 and MS Excel all together for the purpose of analyses. The accuracy of the software was tested by solving some existing problems offered in the textbooks written by those who contributed significantly in the fluid transient area. Comparisons of the results show that the results of the developed software is in good agreement with the solutions given in those books.

Keywords: *Transient Scenarios, Water Hammer, Pipe Flow, Method of Characteristics, Computer Code*

1 Introduction

Devices such as valves, pumps or any other mechanical equipment that can disturb the steady state flow conditions can trigger a transient event. Without precautions these transient events can lead to catastrophic events. For example a hydroelectric power plant in Russia, Sayano-Shushenskaya (2009) was completely destroyed due to sudden stoppage of one of its turbines. As a result, 76 people lost their lives and approximately $310 million worth of damage was inflicted.

The main objective of the transient analysis is to carry out simulations of such situations in advance and enable engineers to take necessary precautions to protect the system. Properly performed analyses will lead to a safer design without the need of over-designing which will guarantee better system control and engineers can judge the situation more in depth with the known pressure and discharge information obtained from such simulations.

Koç (2007) developed a computer code to analyze fluid transients. Method of Characteristics were used to solve partial differential equations and computer code is written in C# programming language.

Bozkuş (2008) analyzed water hammer problems in Çamlıdere – İvedik Water Treatment Plant Pipeline. He simulated a valve closure scenario for this pipeline using a computer code written in Fortran programming language. As a result of his research optimum valve closure times were found for the safe operation of this pipeline.

Dursun (2013) investigated a method of protection for water hammer problems in Yesilvadi Hydropower Plant. They simulated the instant load rejection of this power plant with and without a pressure relief valve and compared the results. From comparison it is seen that pressure relief valves are effective in decreasing turbine runaway speed however, incorrect operation of these valves causes higher transient pressure waves.

Bozkuş et al. (2016) investigated performance of a pumped discharge line with joint use of protective devices against water hammer. From their research it was found that without protective devices pipe system experiences very low pressures and in some cases it is below vapor pressure of the liquid. Moreover, further investigations are conducted adding protective devices to the system such as flywheel, air chamber and in-line check valves. As a result, they found out that single use of these protective devices are economically inefficient whereas joint use of in-line check valves and air chambers results in more economical and safer design.

Bozkuş and Dinçer (2016) investigated water hammer problems in Wind-Hydro Hybrid power plants. They used commercially available software to solve water hammer events caused by sudden load rejection of power plant turbine with and without surge tank and compared the results.

Apart from academical studies there are also commercial software in this field such as Bentley Hammer(2017) and Wanda (2017). They are capable of simulating transients for pipe networks and pipelines including large variety of boundary conditions.

In the present study, Dalgıç (2017), under the supervision of Dr. Bozkuş, has developed a computer software for the purpose of establishing different scenarios and conducting transient simulations. The preferred solution approach for this software is the method of characteristics which solves non-linear continuity and conservation of momentum partial differential equations in space and time. Variety of boundary conditions are introduced to the software enabling user to obtain solutions to the transient scenarios.

Moreover, this software utilizes AutoCAD's powerful graphical and drawing capacity to create scenarios which is very practical as well as it uses Microsoft Excel as its database to store results of the analysis which would be very practical for design engineers. The list given below explains briefly what H-Hammer software is capable of;

- It can create a topography of the pipe route from AutoCAD drawing model.
- It has the advantage of using AutoCAD utilities allowing user to create their scenarios in an infinite model space which eases users' experience for creating schematics.
- Its schematic views of the scenarios are user friendly and easy to assemble.
- It can calculate pressure wave speed for given parameters, time interval, distance intervals (mesh size) for the given parameters.
- It can calculate friction factor by Colebrook-White equation.
- It can calculate pump moment of inertia and other required pump parameters by empirical formulas which are useful in case user is not able to receive experimental data from manufacturer.
- It will combine real pipe profile elevations and pressure values obtained from transient analysis to make cavitation analysis and stress analysis.
- As a result of cavitation and stress analysis it will calculate necessary pipe thicknesses and signal the cavitation locations and durations.
- It has powerful graphing options which enable user to plot graphs of pressure vs. time, pressure vs. distance, discharge vs. time and discharge vs distance.
- It can animate the motion of pressure waves upon completion of analysis and compare this motion in combination with the pipe profile drawn by the user on AutoCAD.

2 Computational Model

The model implements the use of explicit method of characteristics (MOC) which were explained in detail by Wylie and Streeter (1983). Basis of explicit method of characteristics are continuity and conservation of momentum equations written in partial differential form.

These partial differential equations can be illustrated as shown in Eqns (1 - 2). Eqn (1) is continuity and Eqn (2) is conservation of momentum equation in which dependent variables are P and V, pressure and velocity respectively.

$$\frac{1}{\rho}\left(\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x}\right) + a^2\frac{\partial V}{\partial x} = 0 \qquad \textbf{(1)}$$

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{4\tau_w}{\rho D} + g\sin\theta = 0 \qquad \textbf{(2)}$$

where,

a= Pressure wave speed, ρ= Fluid density, τ_w= Wall shear stress, D= Diameter of the pipe, g= Gravitational acceleration, θ = Inclination angle of the pipe with respect to horizontal axis.

These two partial differential equations are transformed into four ordinary differential equations by using the method of characteristics as shown in Eqns (3 – 4).

$$\left.\begin{aligned}&\frac{dx}{dt} = V + a\\&\frac{1}{\rho}\frac{dP}{dt} + a\frac{dV}{dt} + aF = 0\end{aligned}\right\} : C^+ \qquad \textbf{(3)}$$

$$\left.\begin{aligned}&\frac{dx}{dt} = V - a\\&\frac{1}{\rho}\frac{dP}{dt} - a\frac{dV}{dt} - aF = 0\end{aligned}\right\} : C^- \qquad \textbf{(4)}$$

where,

$F = \frac{4\tau_w}{\rho D} + g\sin\theta$

By integrating these ordinary differential equations, numerical solutions are obtained for C^+ and C^- characteristics lines by inserting discharge Q and piezometric head H, instead of V and P respectively, as shown in Eqns (5 – 6).

$$C^+ : H_{Pi} = C_P - BQ_{Pi} \quad \text{and} \quad C_P = H_{i-1} + BQ_{i-1} - RQ_{i-1}|Q_{i-1}| \qquad \textbf{(5)}$$

$$C^- : H_{Pi} = C_M + BQ_{Pi} \quad \text{and} \quad C_M = H_{i+1} - BQ_{i+1} + RQ_{i+1}|Q_{i+1}| \qquad \textbf{(6)}$$

in which

$$B = \frac{a}{gA} \quad \text{and} \quad R = \frac{f\Delta x}{2gDA^2}$$

where f is the friction factor in the pipe, Δx is the distance increment and A is the cross sectional area of the pipe.

Figure 1 illustrates grid structure of solution by characteristics lines at an instant at point P. Typically, dependent variables H and Q are known at time t=0, called initial conditions. Then, solution starts from the known values of Q_{A_t}, H_{A_t}, Q_{B_t}, H_{B_t} at time t and proceeds to find the unknown $Q_{P_{t+\Delta t}}$, $H_{P_{t+\Delta t}}$ values at point P. Moreover, for every node along the pipeline the similar kind of calculations are done over time and space but there might be boundaries on some nodes and these boundaries must also be implemented through the solution matrix. In order to satisfy accuracy of the solution Courant condition should be satisfied which states that

$$\frac{\Delta x}{\Delta t a} \leq 1$$

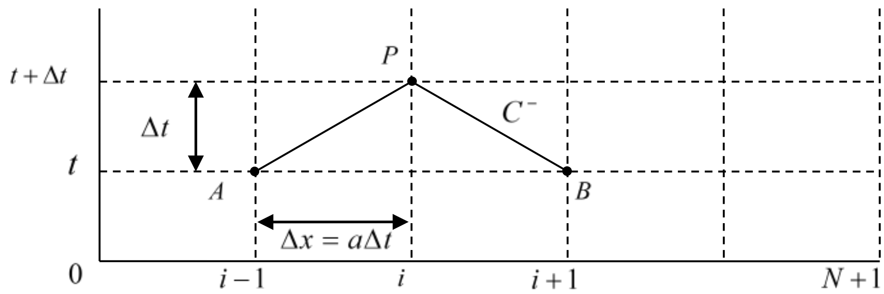

Figure 1 Characteristics lines for point solution in x-t plane

3 Developed Computer Code

Computer code developed in this study is able to implement below boundary conditions in simulations;

- Pipe Section
- Series Junction
- Branching Junction
- Upstream Reservoir with Constant Head
- Upstream Reservoir with Variable Head
- Centrifugal Pumps (Single-Series-Parallel Connected)
- Air Chamber with Orifice
- Interior Valve
- Downstream Valve
- Surge Tank with Standpipe
- Downstream Reservoir with Constant Head
- Downstream Dead End
- Air Chamber with Standpipe
- Surge Tank with Throttled Orifice

In the next sub sections user interface and other functions of the code will be explained.

3.1 Main User Interface

On main user interface all menus are available for usage. All of these menus serve to different purposes. Names of the menus are given below and image of main screen can be seen on Figure 2.

- Files
- Topography
- Material/Liquid Information
- Pressure Wave Speed Calculations
- Friction Factor Calculator
- Stress Analysis
- Pump Calculations
- Air Chamber Design
- Create Graph
- Animation

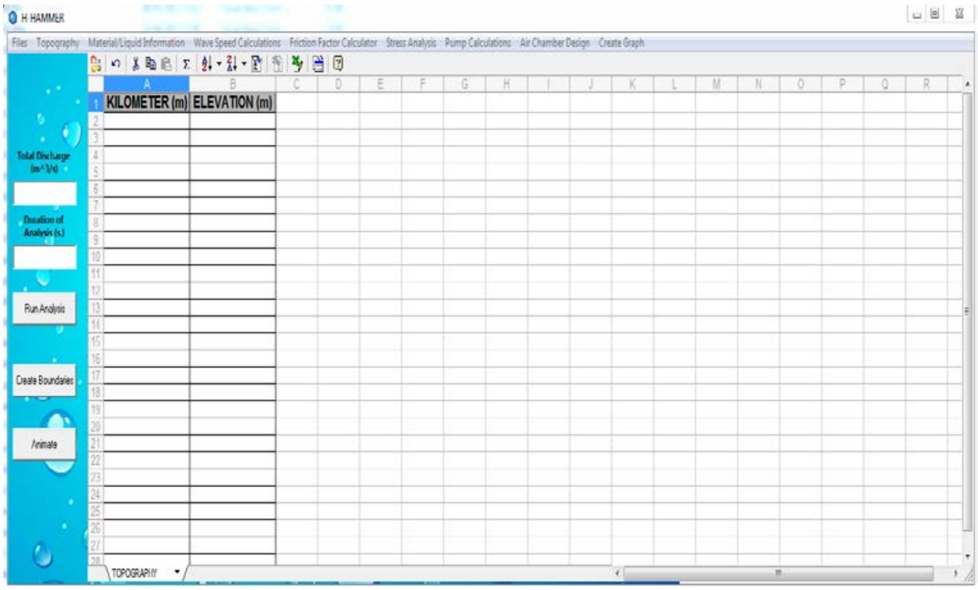

Figure 2 H-Hammer main interface

4 Verification of the Code

Many scenarios were performed to test the accuracy of the code developed. In this paper, only one of them will be presented due to the space limitations.

4.1 Scenario: Pump Trip with a Valve

In the first case the results of a program titled Whammer written by D.C. Wiggert (1984) from Michigan State University will be compared with the program, H-Hammer developed in the present study. Whammer was written in Fortran programming language and is designed to analyze pump failure transients with or without a valve located just downstream of the pump. In this comparison output of Whammer is obtained by running it in executable format. At the end outputs of the two programs are compared. Figure 3 illustrates schematic of pump trip scenario. Table 1 outputs input data for the pump trip. Some of the results are compared on Figures 4 through 8.

Figure 3: Schematic of pump trip scenario

Table 1: General input data for pump (failure with valve in front scenario)

Pipe Length, L	10,000	m
Diameter of Pipe, D	0.65	m
Acoustic speed, a	1320.92	m/s
Friction Factor, f	0.022	
Density of Water, ρ	1000	kg/m^3
Hoop Stress of Pipe, σ	35	MPa
Rated Head of Pump, H_R	85	m
Rated Discharge of Pump, Q_R	0.10	m^3/s
Rated Speed of Pump, N_R	885	rpm
Rated Torque of Pump, T_R	1056.40	N.m
Rated Efficiency of Pump, η_R	0.85	
Valve Minor Loss Coeff.	3	
Value of D/e	20	
Value of WR^2	200	Nm^2
Elasticity Modulus of Pipe Material	170	GPa
Bulk Modulus of Elasticity of Fluid	2.19	GPa

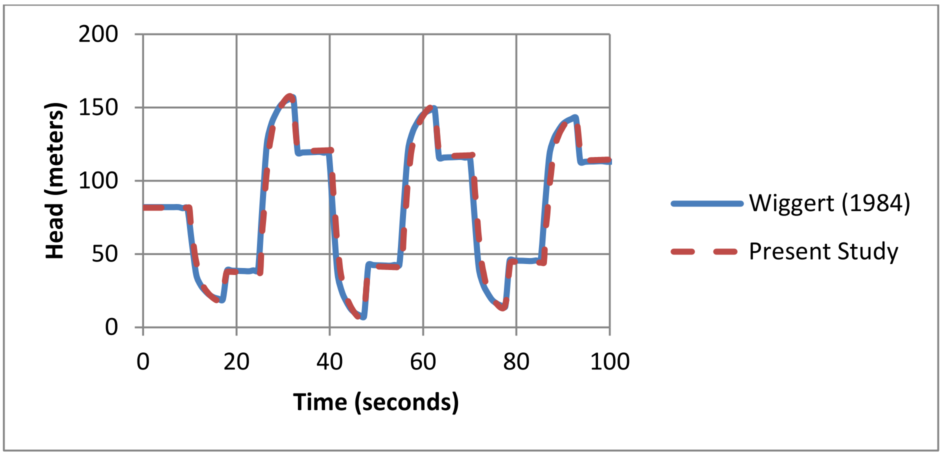

Figure 4: Head vs time graph for pump trip with valve at x=0+000 m

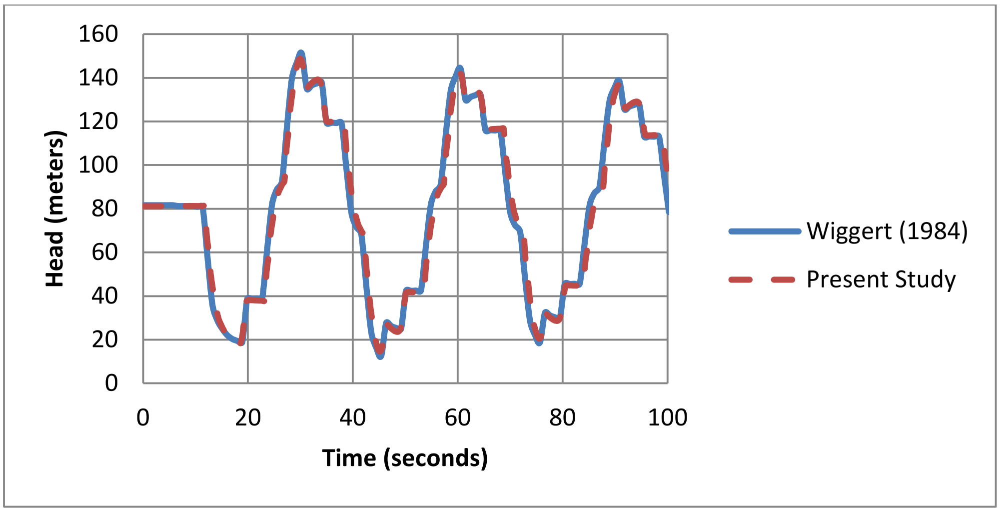

Figure 5: Head vs time graph for pump trip with valve at x=2+500 m

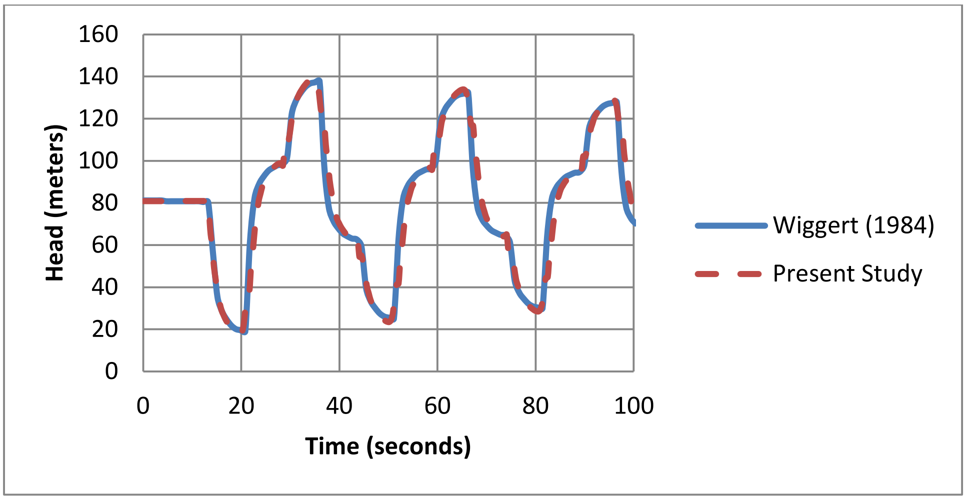

Figure 6: Head vs time graph for pump trip with valve at x=5+000 m

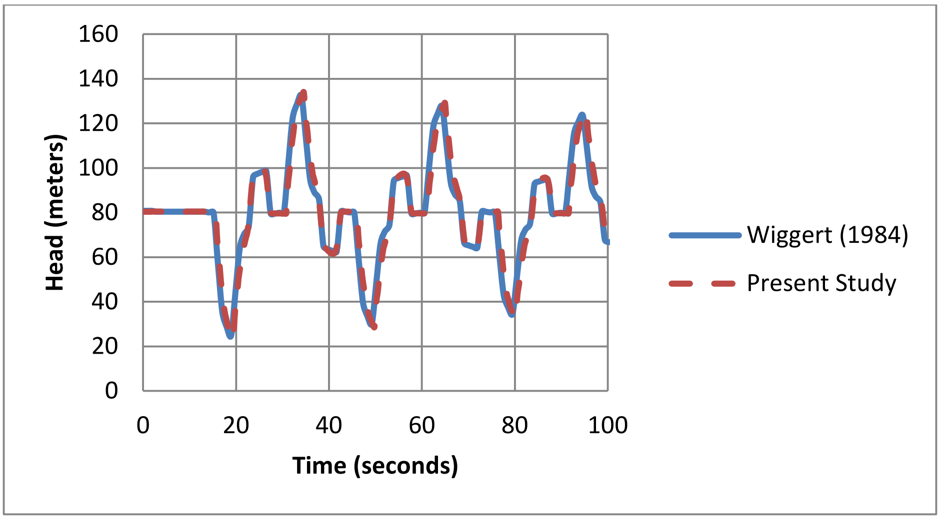

Figure 7: Head vs time graph for pump trip with valve at x=7+500 m

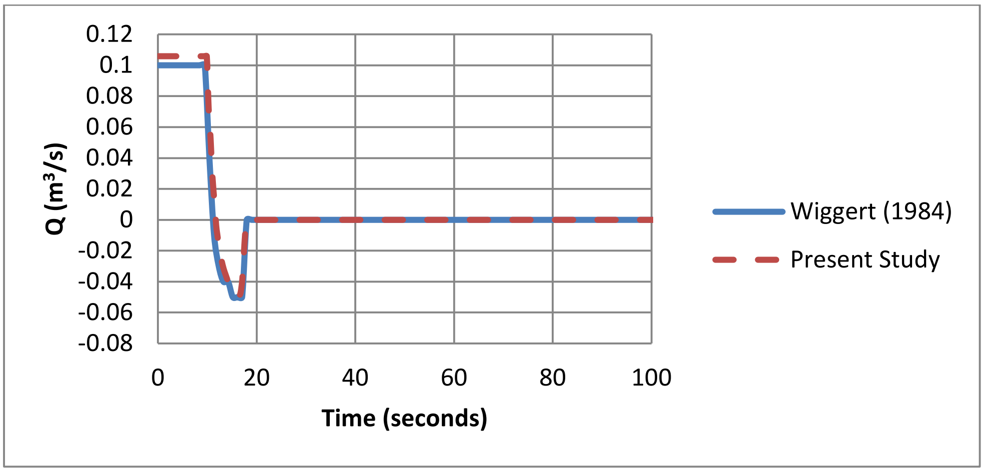

Figure 8: Discharge vs time graph for pump trip with valve at x=0+000 m

5 Conclusions and Suggestions

In the present study, a code was developed to solve a large variety of fluid transient problems. The method of characteristics was used to solve the basic unsteady pipe flow equations. Most commonly encountered boundary conditions were inserted into the code, which are: Series Junction, Branching Junction, Upstream Reservoir with Constant Head, Upstream Reservoir with Variable Head, Centrifugal Pumps (Single-Series-Parallel Connected), Air Chamber with Orifice, Interior Valve, Downstream Valve, Surge Tank with Standpipe, Air Valve, Downstream Reservoir with a Constant Head, Downstream Dead End, Air Chamber with Standpipe and Surge Tank with Throttled Orifice, etc.

The code requires and makes use of Autocad, MS Excel and Visual Basic 6.0 programs together to perform the simulations and present the output in a professional-looking way. The accuracy of the code was verified by performing a number of simulations of the problems found in some well-known fluid transient textbooks. Comparisons showed that the results of the code developed in the present study are in very good agreement with those of the textbooks.

The program capabilities were detailed in the present study by Dalgıç (2017). Needless to say, the code still requires further improvements, new boundary elements and other contributions may be added in the future. It is deemed that a good step was taken in the right direction to develop eventually a relatively sophisticated fluid transient code which would be beneficial to the design engineers working in this field.

References

Bentley Hammer. Hammer Water Hammer and Transient Analysis Software (2017). http://www.bentley.com/en/US/Products/HAMMER/Product

Bozkuş, Z. (2008). Water Hammer Analyses of Çamlıdere-İvedik Water Treatment Plant (IWTP) Pipeline. Teknik Dergi Vol. 19, No. 2 April 2008, pp:4409-4422

Bozkuş, Z., Çalamak, M., Rezaei, V. (2016). Performance of a Pumped Discharge Line with Combined Application of Protection Devices Against Water Hammer. KSCE Journal of Civil Engineering (2017)21(4):1493-1500

Bozkuş, Z., Dinçer, A.E. (2016). Investigation of Water Hammer Problems in Wind-Hydro Hybrid Power Plants. Arabian Journal for Science and Engineering DOI 10.1007/s13369-016-2142-2

Dalgıç, H. (2017). Development of a Computer Code to Analyze Fluid Transients in Pressurized Pipe Systems. M.S. Thesis, Middle East Technical University, Ankara-Turkey.

Dursun, S. (2013). Numerical Investigation of Protection Measures Against Water Hammer in the Yesilvadi Hydropower Plant. M.S. Thesis, Middle East Technical University, Ankara-Turkey.

Koç, G. (2007). Simulation of Flow Transients in Liquid Pipeline Systems. M.S. Thesis, Middle East Technical University, Ankara-Turkey.

Victor S. Seleznev, Alexey V. Liseikin, Alexey A. Bryksin, Pavel V. Gromyko (2014); What Caused the Accident at the Sayano–Shushenskaya Hydroelectric Power Plant (SSHPP): A Seismologist’s Point of View. Seismological Research Letters ; 85 (4): 817–824. doi: https://doi.org/10.1785/0220130163

Wanda transient simulation software (2017). https://www.deltares.nl/en/software/wanda/

Wiggert, D.C. (1984). Single Pipeline Water Hammer Program, Whammer. Michigan State University.