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Development of Numerical Model to Compute Water Hammer Transients in Pipe Flow

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***Abstract*—**Water hammer is a hydraulic transient problem which is commonly encountered in the penstocks of hydropower plants. The numerical model was developed to estimate the transient behavior of pressure waves in pipe systems. The computational algorithm was proposed to model the water hammer phenomenon in a pipe system with pump shutdown at midstream and sudden valve closure at downstream. To predict the pressure head and flow velocity as a function of time as a result of rapidly closing a valve and pump shutdown, two boundary conditions at the ends considering pump operation and valve control can be implemented as specified equations of the pressure head and flow velocity based on the characteristics method. It was shown that the effects of transient flow make it determine the needs for protection devices, such as surge tanks, surge relief valves, or air valves, at various points in the system against overpressure and low pressure. It produced reasonably good performance with the results of the proposed transient model for pipeline systems. The proposed numerical model can be used as an efficient tool for the safety assessment of hydropower plants due to water hammer.

***Keywords*—**Water hammer, hydraulic transient, pipe systems, characteristics method.

I. INTRODUCTION

THE field of hydroelectric power plants is continuing to grow steadily in South Korea when considering climate change and securing energy so that safety assessment technology for facilities has emerged as a serious problem in recent year. Water hammer significantly affects the safety of piping equipment and component, caused by fluctuations of flow velocity and pressure during delivering plant discharge in hydropower facilities. Water hammer is the phenomenon of the propagation of high pressure and negative pressure wave when there is an instantaneous variation in the velocity or pressure in steady-state flow conditions. The most common causes of these fluctuations are sudden closure of a valve, shutdown of a pump or turbine [1]. In this study, the numerical solution scheme for simulating transient pipe flow after identifying the mechanism of water hammer occurrences was constituted, then numerical transient model was developed by implementing boundary conditions for reservoir, valve and pump. In addition, the numerical model performance was calibrated by simulating hydraulic transient due to water hammer imposing simple boundary conditions.

II. MECHANISM OF WATER HAMMER OCCURRENCE

In order to understand the mechanism of the water hammer better, a piping system having a valve shown in Fig. 1 is considered. The flow inside the pipeline is instantaneously stopped when the valve is rapidly closed. Consequently, the pressure rise ΔH along the pipe causes, and pressure wave propagates towards the downstream with relatively low pressure. Then, as the pressure rises in the upstream end, a pressure wave reaches the valve again to maintain the steady-state conditions. As these processes are repeated for the next period, the pressure inside the pipe gradually reached the eventual steady state. The transient flow is changed in time period of L/a, until a steady-state is achieved.

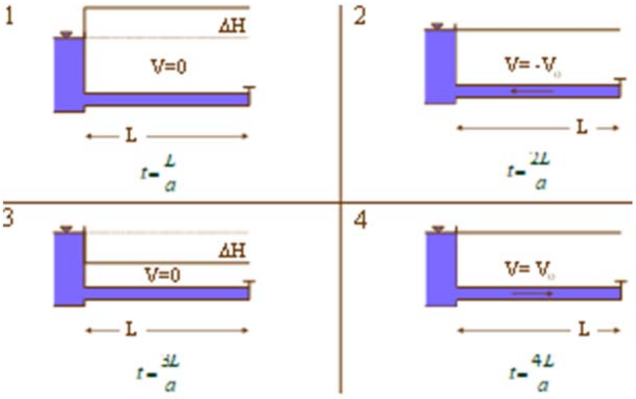

Fig. 1 Water hammer mechanism in single pipe system [2]

The high-pressure head ΔH caused by the sudden closure of a valve propagates at the wave speed a. The wave speed is the wave celerity as a relative velocity that pressure is propagated. The wave celerity can be calculated by using the concept of transient elasticity and determined by pipe wall thickness, the wall material, the bulk modulus of elasticity of the fluid, and Poisson's ratio, which is given by

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+\frac{KD}{Ee}}} \qquad (1)$$

where a = propagation speed of pressure wave; ρ = density of fluid; K = the bulk modulus of elasticity; e = the pipe wall thickness; D = diameter of the pipe.

III. GOVERNING EQUATIONS

The water hammer equations are one-dimensional unsteady pressure flow equations given by [3]

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$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}+V\sin\theta+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \quad (2)$$

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{fV|V|}{2D}=0 \quad (3)$$

where, H= pressure head; V= flow velocity; θ = pipe slope; g = acceleration of gravity; t = time; f = Darcy-Weisbach friction factor; x = distance along the pipe.

IV. METHOD OF CHARACTERISTICS TRANSFORMATION

The Method of Characteristics (MOC) is most popular approach to convert the two partial differential equations of continuity and momentum (2) and (3) into ordinary differential equations along characteristics line [4]. Both equations are presented as the integrated compatibility equations for pressure H_P and velocity V_P,

$$H_P=\tfrac{1}{2}\left[\tfrac{g}{a}\left(V_{Le}-V_{Ri}\right)+\left(H_{Le}+H_{Ri}\right)-\tfrac{g}{a}\tfrac{f\Delta t}{2D}\left(V_{Le}\left|V_{Le}\right|-V_{Ri}\left|V_{Ri}\right|\right)\right] \quad (4)$$

$$V_P=\tfrac{1}{2}\left[\left(V_{Le}+V_{Ri}\right)+\frac{g}{a}\left(H_{Le}-H_{Ri}\right)-\tfrac{f\Delta t}{2D}\left(V_{Le}\left|V_{Le}\right|+V_{Ri}\left|V_{Ri}\right|\right)\right] \quad (5)$$

V. IMPLEMENTATION OF BOUNDARY CONDITIONS

To implement boundary conditions for a single pipe system, the upstream boundary condition can be considered as the prescribed velocity and head at the reservoir given by

$$V_{P1}=V_2+\tfrac{g}{a}\left(H_0-H_2\right)-\tfrac{f\Delta t}{2D}V_2\left|V_2\right| \quad (6)$$

$$H_{P1}=H_0 \quad (7)$$

Also, the downstream boundary condition can be specified as the prescribed pressure head of the valve given by

$$H_{P_{N+1}}=H_N-\tfrac{a}{g}\left(V_{P_{N+1}}-V_N\right)-\tfrac{a}{g}\tfrac{f\Delta t}{2D}V_N\left|V_N\right| \quad (8)$$

Meanwhile, for the implementation of boundary condition for a pump, a single non-linear equation in Q is obtained by combining the equations governing the flow at upstream of a pipe [5],

$$H_P=A'Q^2+B'Q+C' \quad (9)$$

where A', B', and C' are the constant parameters of the pump.

On further substituting of $Q=V_{P1}A$ and $H_P=H_{P1}-H_{\Sigma P}$, it can be arranged as:

$$H_{P1}=AV_{P1}^2+BV_{P1}+C \quad (10)$$

So, the required quadratic equation can be solved for V_{P1} and hence H_{P1} from (10).

$$\left(\tfrac{g}{a}A_P\right)V_{P1}^2+\left(\tfrac{g}{a}B_P-1\right)V_{P1}+\left(V_2+\tfrac{g}{a}C_P\tfrac{g}{a}H_2-\tfrac{f\Delta t}{2D}V_2\left|V_2\right|\right)=0 \quad (11)$$

VI. COMPUTATIONAL ALGORITHM

A numerical simulation model was developed to predict water hammer in single pipe systems in this work. Its computational algorithm was constructed based on MOC-FDM (Finite Difference Method). The numerical solution for water hammer in single pipe systems can be used to handle pressure transients with steady friction for controlling a valve and pump. Firstly, the global parameters, such as the properties of the pipe and fluid, are set and the computational grid is generated, which is used to calculate the initial value, the suction head of pump. After all the preparation of calculation, computation starts to time marching loop, calculating the suction head from the solution from previous time step. The calculated suction head and data from the previous time step are then used to predict the velocity and pressure behaviors for the current time step from (4) and (5). Thereafter, the current step saves the necessary data and step forward in time. The computational algorithm used for the MOC implementation of unsteady flow model is presented in Fig. 2.

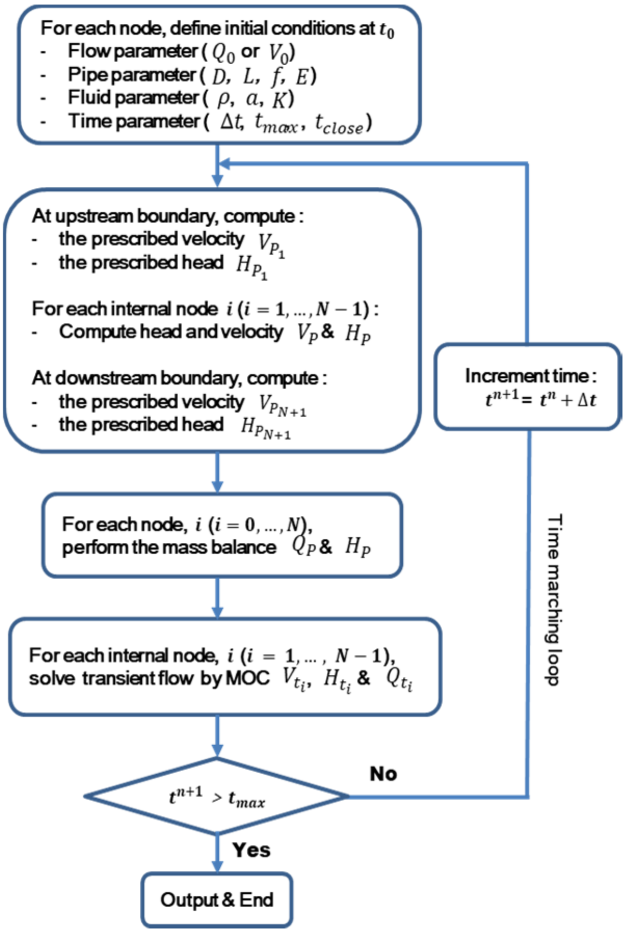


Fig. 2 The flow chart of computational algorithm

VII. NUMERICAL SIMULATION FOR MODEL VERIFICATION

In order to verify the developed numerical algorithm for transient flow, two case studies were simulated: (1) the sudden closure of a downstream valve; and (2) pump shut down during steady-state operation.

Case 1: Sudden Closure of a Downstream Valve

A pipeline system setup is composed of a 1,500 m long pipeline with an inner diameter of 0.8 m and a friction loss factor of 0.02 connecting a reservoir (water level = 220 m) on its upstream end and a valve on its downstream end (Fig. 3). The pipe level at the inlet and outlet ends of the pipeline is 30 m and 15 m, respectively. The initial conditions specify all velocities to be 1.5 m/s. The pressure wave speed is assumed to be 750 m/s. In order to simulate transients for this case, two different times of linear valve closure were applied for 5 and 10 seconds. The simulation results for the valve closure show that the transient behavior of pressure heads and velocity along the pipeline can be seen in Fig. 4. From this figure, the head amplitude from an overpressure to low pressure was changed in an 8 seconds period. A rapid closure (5 seconds) results in a shorter period in a cycle of fluctuation of head and velocity. It was shown that the amplitude of pressure and velocity oscillation during water hammer was increased by more than twice compared to the 10 seconds closure, which indicated the shorter the closure time, the greater the pressure head rise inside the pipe. In addition, it is found that the flow velocity fluctuation is greater than the pressure fluctuation at the upstream end of the pipe and the amplitude of pressure head is gradually increased towards the downstream valve.

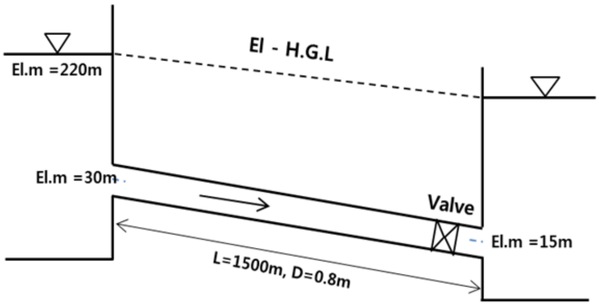
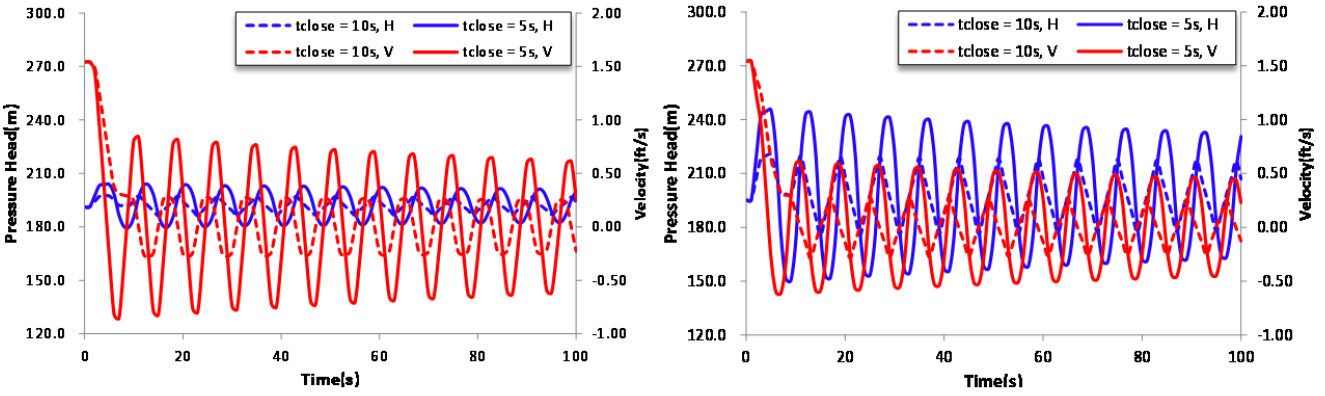
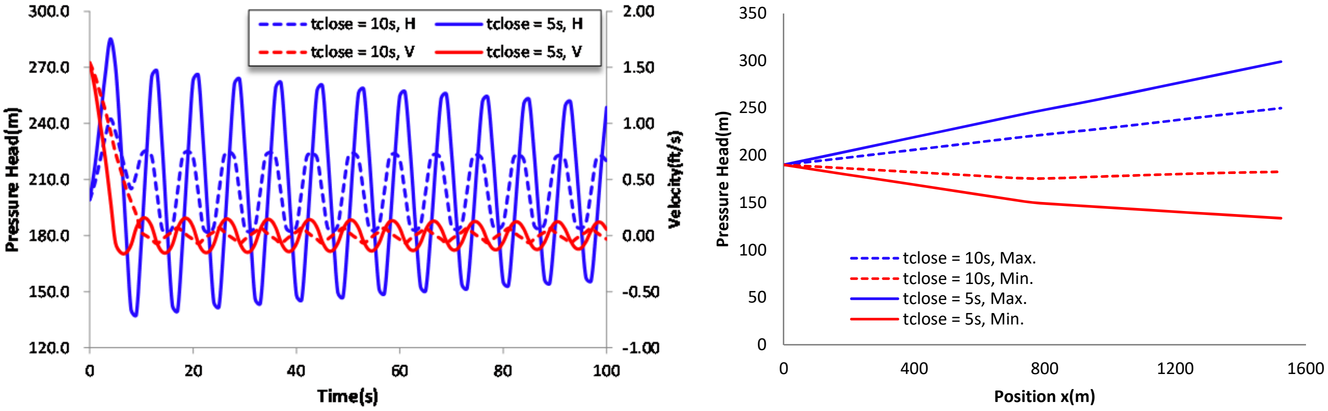


Fig. 3 The reservoir valve system



(a) Upstream reservoir

(b) Midstream pipe



(c) Downstream valve

(d) Hydraulic grade line

Fig. 4 Transients in a reservoir valve system (sudden valve closure)

Case 2: Pump Shutdown during Steady-State Operation

Centrifugal pump pipeline's length is 4,500 m, which is connected with a constant water level of 300 m reservoir; outlet pipeline's length is 9,000 m, which is connected with constant water level of 340 m reservoir (Fig. 5). The inner diameter of whole pipeline is 0.6 m, and friction loss factor is 0.013. The initial conditions are assumed: the steady-state velocity of 1.5 m/s and pressure wave speed of 1,100 m/s. The pipe level at the inlet and outlet ends of the pipeline is 250 m and 380 m, respectively. This case study demonstrates the capability of the developed algorithm to analyze the water hammer effect by simulating the sudden pump shut down at the midstream of a pipeline. Fig. 6 shows the difference between the maximum and minimum pressure head is significantly large at inlet and outlet of pump. Since pump stopping, the pressure head at the pump inlet rises, then rising pressure head is offset as negative pressure wave reach to reservoir. On the contrary, pressure head is decreased towards the pump and gradually attenuated by head loss as repeating the process. In addition, it is found that the variation of the pressure head rise at the outlet pipe is larger than those of inlet pipe and obtained reasonable results. Meanwhile, the velocity is gradually decreased due to pump deceleration and velocity change around pump becomes zero.

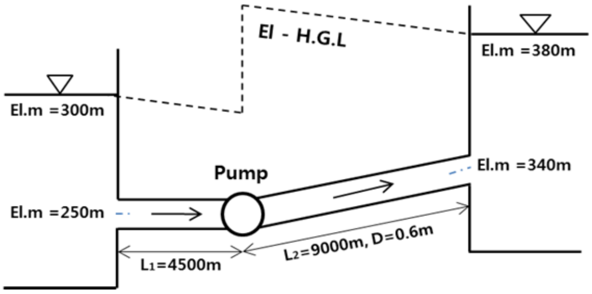
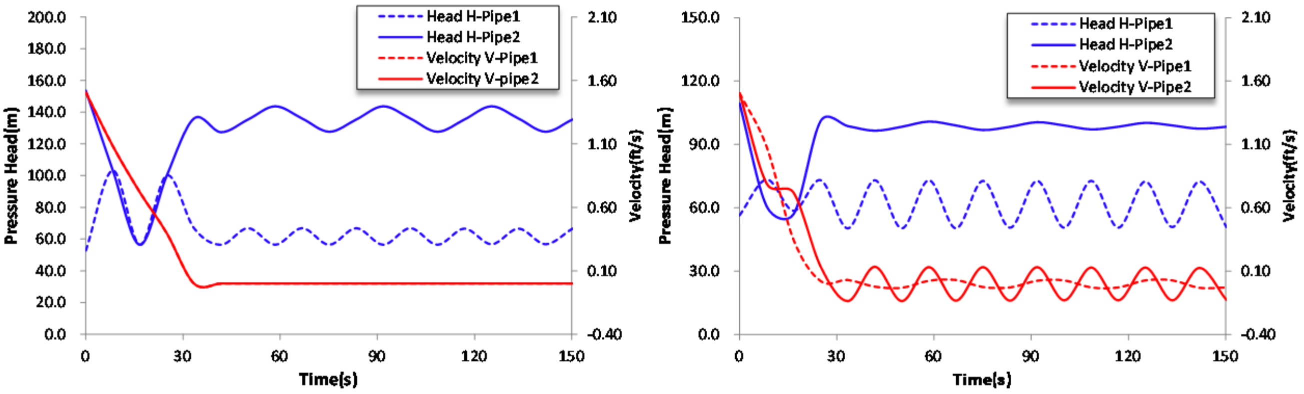
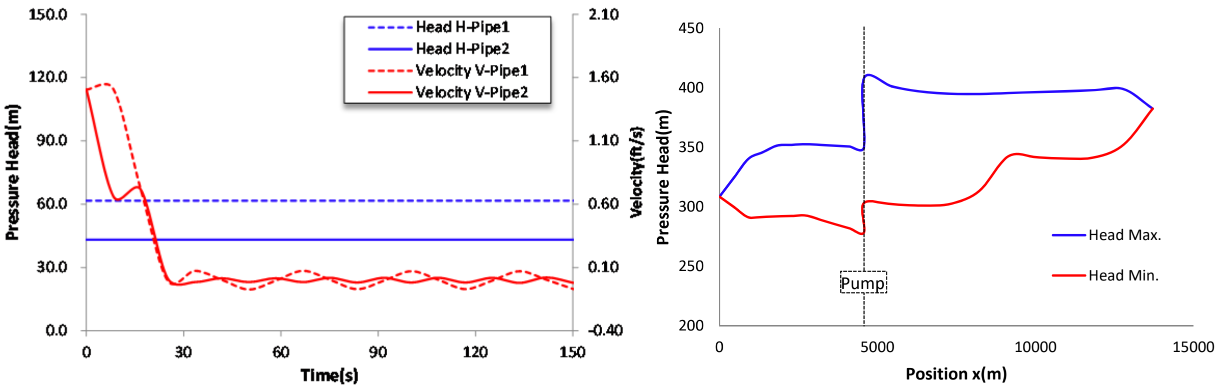


Fig. 5 The reservoir-pump system



(a) Just upstream/downstream of pump

(b) Midstream pipe



(c) Upstream/downstream reservoir

(d) Hydraulic grade line

Fig. 6 Transients in a pumping system (pump shut down)

Fig. 6 (d) shows that the maximum and minimum pressures are presented along the pipeline. For this case, the pressure head rises in pump and the pressure head is gradually decreased so that pressure wave propagates towards the reservoir again, because pump work plays a role in rising pressure head.

VIII. CONCLUSIONS

The mechanism for water hammer occurred in pipeline system was identified and transient analysis model was developed for safety assessment in this study. The proposed model which was written in FORTRAN code was used to perform water hammer simulation for two cases. The numerical simulation results show variation of pressure head and velocity is reasonably predicted for hydraulic transient process under conditions of test cases. In case 1, the behavior of the hydraulic transient for two different times of linear valve closure applied for 5 seconds and 10 seconds was studied. It was showed that the amplitude of pressure and velocity fluctuation caused by water hammer for 5 seconds closure was increased by more than twice compared to the 10 seconds closure. Case 2 describes a general hydraulic transient problem due to pump shut down during steady-state operation. The simulation results indicate that the pressure head at the pump inlet increases and negative pressure wave propagates towards the downstream reservoir, then the pressure head was decreased along the pipeline. Consequently, the result of this study will contribute to reduce the risk of system damage or failure in the penstocks during operation of hydropower plants.

ACKNOWLEDGMENT

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