Computer Modelling of Hydraulic Transients in Pipe Networks and the Associated Design Criteria

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ABSTRACT Sudden changes or the stoppage of flows in pipeline systems causes a hydraulic transient or water hammer event. Kinetic energy is destroyed during the change and is converted into pressure energy, which is transmitted as a pressure or water hammer wave in the pipeline system. The water hammer wave often generates the maximum pressure in pipeline systems. The maximum pressure governs the design of pipeline networks including the selection of pipe diameters, pipe wall thicknesses and water hammer control devices. Computer modelling of water hammer in pipeline systems provides a tool for simulation of water hammer events and thus provides a better understanding of the behaviour of the effects of pressure waves. In this paper, details of a computer simulation model, based on method of characteristics for modelling water hammer in water distribution networks is presented. The simulation model has been applied to a low head irrigation system. A question arises as to which water hammer event will cause the most severe pressure in the irrigation network. The water hammer events of closing valves at different locations in the system are considered. The results obtained show that the various water hammer events create different levels of pressure surge in different pipes within the system. An approach for evaluating the impact of the pressure surge is suggested and is used to measure the severity of the water hammer events. This provides engineers with a method for choosing the most critical water hammer event for the comprehensive design of water distribution systems including water hammer.

1. INTRODUCTION

A hydraulic transient phenomenon is defined as unsteady flow or water hammer, which is transmitted as a pressure or water hammer wave in the pipeline system. Water hammer can be generated by operating system devices including valves and pumps, and also by events such as pipe rupture.

A water hammer event is important in design, maintenance and operation of water distribution systems. It can cause high pressures, excessive noise and negative pressures. The pipe can be damaged in the short term through over-pressures, or, in the long term, through cavitation in the pipe. Thus the pipeline should be designed either with a suitable pipe size (both diameter and wall thickness) or with an appropriate water hammer control measure to withstand the associated maximum positive pressure and/or the minimum negative pressures. Computer modelling of water hammer in pipeline systems provides a tool for simulation of water hammer events and thus provides a better understanding of the behaviour of the transmission of the hydraulic transient pressure waves.

Although computer modelling tools for simulation of hydraulic transient flows have been widely used in simple pipeline systems, little is known about the behaviour of the transients flow in a complex network system. It has been recognised that long pipelines of large diameter may experience severe transient pressures. For network systems, there is a feeling that the network (loop) is more robust than a series pipeline. In other words, it has been postulated (Watters 1984) that the network may behave like a reservoir, which splits the water hammer wave into several subwaves and which in turn diminishes the pressure rise. This assumption has been found little rational basis, and recent research results (Karney and McInnis 1990; 1992; McInnis and Karney 1995) suggested that the opposite might be true. It is essential, therefore, that the computerised tool is developed to enable the investigation of transients flow in complex water distribution networks. In this paper, details of a computer simulation model, based on the method of

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characteristics for modelling water hammer in water distribution networks is presented. The computer model has been applied to a low head irrigation system. An approach for evaluating the impact of the pressure surge is suggested and is used to measure the severity of the water hammer events. This provides engineers with a method for choosing the most critical water hammer event for the cost effective transient design of water distribution systems .

2. GOVERNING EQUATIONS

The governing equations for unsteady flow in pipeline are derived under the following assumptions including (1) one-dimensional flow i.e. velocity and pressure are assumed constant at a cross-section; (2) the pipe is full and remains full during the transient; (3) no column separation occurs during the transient; (4) the pipe wall and fluid behave linearly elastically and (5) unsteady friction loss is approximated by steady state losses.

The unsteady flow inside the pipeline is described in terms of the unsteady mass balance (continuity) equation and unsteady momentum equation, which define the state variables of Q (discharge) or V (velocity) and H (pressure head), given as (Wylie and Streeter 1993):

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \qquad (1)$$

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

where x = distance along the pipe; t = time; V = velocity; H = hydraulic pressure head in the pipe; g = acceleration due to gravity; a = wave speed; f = Darcy-Weisbach friction factor; ρ = fluid density and D = pipe diameter.

Eq. 1 is the continuity equation and takes into account the compressibility of the water and the flexibility of the pipe material. Eq. 2 is the equation of motion. The wave speed a is defined as:

$$a^2=\frac{K/\rho}{1+\left[(K/E)(D/e)c_1\right]} \qquad (3)$$

$$c_1=\begin{cases}1 & \text{for expansion joints} \quad \text{when } D/e>25\\ 1.4(2e/D)+D/(D+e) & \text{when } D/e<25\end{cases}$$

where K = bulk modulus of elasticity of the flow; e = pipe wall thickness, E = modulus of elasticity and c_1 = pipe restraint condition factor.

A method of characteristics transformation is applied to the basic Eq. 1 and 2. The ordinary differential equation that is obtained is as follows:

$$\frac{g}{a}\frac{dH}{dt}+\frac{dV}{dt}+\frac{fV|V|}{2D}=0 \qquad (4)$$

This compatibility equation is only valid along the C^+ characteristic equation of :

$$\frac{dx}{dt}=+a \qquad (5)$$

The other ordinary differential equation obtained is given as:

$$-\frac{g}{a}\frac{dH}{dt}+\frac{dV}{dt}+\frac{fV|V|}{2D}=0 \qquad (6)$$

This compatibility equation is only valid along the C^- characteristic equation of:

$$\frac{dx}{dt}=-a \qquad (7)$$

The differential equations (4) and (6) are solved at the intersection of C^+ and C^- characteristic lines given by equations (5) and (7).

3. MODEL IMPLEMENTATION

A transient model (Simpson et al. 1992), originally developed for water hammer simulation of hydro-electrical power plant systems, was based on the method of characteristics. This method was used to solve the unsteady continuity equation and unsteady equation of motion governing flow and pressure head variation in the networks. For flow elements where non-linear equations are added to the method of characteristics equations—a set of nonlinear equations results. A Newton-Raphson iterative solution procedure is used to solve for the unknown variables for each flow element and/or boundary condition.

The transient solution, based on the method of characteristics, proceeds point by point. Each pipe in the network is divided into an even number of reaches. Head and discharge conditions are solved for at the end of each reach (called sections). These sections constitute interior points. Each interior point in a pipe is solved for at every second time step for the head and flow independently of other points in the system. A non-pipe element such as a junction, reservoir, valve or surge tank is referred to as a particular boundary condition and is solved simultaneously for all the variables associated with that boundary condition.

The existing transient model has been improved for the transient simulation of water distribution systems in this study. The model has been enhanced to be more robust at handling surge tanks, different pipe materials, wave speeds, pipe-end valves and valve operations. The enhanced transient model is integrated with a hydraulic network solver EPANET (Rossman 1994), which is employed for simulating steady state flow in the network to establish the initial flow conditions for the transient simulation. The integrated computer model is then to simulate the hydraulic transient of the water distribution networks with reservoirs, nodes and/or junctions, in-line valves, pipe-end valves and surge tanks.

4. LOW HEAD IRRIGATION SYSTEM

Irrigation areas are usually supplied by reservoirs (or storage tanks) at the upstream end of an irrigation distribution network. In a low pressure system, the minimum permissible pressure head is usually in the order of 2 to 5 meters. Velocities depend on the particular location of a pipe and the demand distribution in the network. A sudden change of the water demand by an irrigator, for instance by closing the valve, may cause a severe water hammer pressure. Thus the system must be designed in such a way that the pipeline can sustain the maximum water hammer pressure. The computer model described above has been applied to simulating the transient behaviour of a low head irrigation system. A comprehensive investigation of different water hammer events has been carried out to identify the critical water hammer loading for the system design.

4.1 System description

An actual irrigation system, called Cobdogla irrigation network as shown in Figure 1, has been chosen as a case study in this paper. Cobdogla irrigation area is part of the Loveday Division adjacent to the River Murray in the Riverland region of South Australia. It is managed by the South Australia Water Corporation. Most of the system was constructed in 1920's. An extensive rehabilitation of the existing aged pressurised system is presently being undertaken. The current study of the transient simulation will contribute to a better understanding of the system behaviour under possible water hammer loadings. It will also provide engineers with a design criteria for the determination of the cost effective selection of water hammer control.

4.2 Transient events and boundary conditions

The possible water hammer events for this case study are sudden change of water demand i.e. closing the valve at the outlet from the pipeline. The boundary conditions associated with the simulation of the water hammer events in the Cobdogla irrigation system are the reservoir and the outlet valve in the network.

There are 11 operating valves considered in this study. The valves are at nodes 28, 31, 34, 11, 14, 40, 49, 43, 44, 46 and 48 as shown in Fig.1. The transient that results by operating each of the valves is independently simulated. In other words, for the simulation of the transient behaviour generated by operating each of the 11 valves, only one valve is assumed being fully opened and water hammer is created by instantaneous closure of that valve. A steady state simulation is performed for each fully opened valve to establish the initial flow condition for the water hammer simulation, and then the transient simulation is carried out for the instantaneous closure of the valve.

4.3 Transient evaluation

In proceeding with the analysis of the different water hammer events, a question arises as to how to measure the severity of a specific transient event. The severity of the transient event can be evaluated not only in terms of the magnitude of the maximum water hammer pressure generated by the event, but also the region of the network affected by the event. Thus a measure for evaluating the severity of the transient event is introduced as the total length of the pipes where the maximum associated pressure is greater than a certain pressure threshold. It is given as follows.

$$L_{effected} = \sum_{i=1}^{T} l_i \qquad when \quad H_i^{max} > H_{threshold} \qquad (8)$$

where $L_{effected}$ = total length of pipes affected by water hammer events; l_i = length of pipe i; H_i^{max} = the maximum transient pressure of pipe i; $H_{threshold}$ = transient pressure threshold and T = total number of pipes.

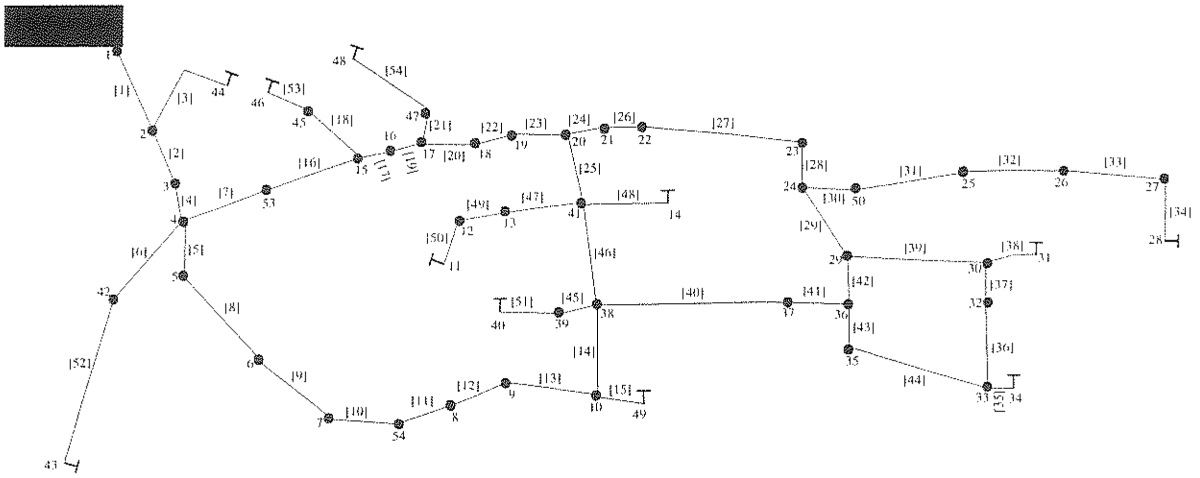

Figure 1 Layout of Cobdogla irrigation network

4.4 Simulation results

A comprehensive investigation of the transient events caused by operating 11 valves in 11 diferent transient runs has been carried out for Cobdogla irrigation network. Two diferent pipe materials have been considered including reinforced concrete pipes and Hobas pipes. The modulus of elasticity (E) of these two materials is quite different, and thus contributes to different wave speeds. For the reinforced concrete, $E = 45\times10^9$ Pa while for Hobas $E = 10\times10^9$ Pa.

The transient events are evaluated by the measure described above with pressure head threshold of 40 meters. As shown in Fig. 2, the operation of valve 28 generated the most severe transient pressure for both reinforced concrete and Hobas pipes. The transient in the network of reinforced concrete pipes is much more severe than the Hobas pipes case for all the water hammer events. Although the total length of the pipes affected by the water hammer event caused by an instantaneous closure of valve 28, 31, 34, 11, 14, 40 is very much same, the locations of pipes affected by the valve closure are different. The maximum transient pressure normally occurs just upstream of the valve which has closed. Figure 3 shows that reinforced concrete and Hobas pipes have a similar transient behaviour for the same water hammer event, but different magnitude of transient pressure due to the different modulus of elasticity of pipe materials. This implies that a severe hydraulic transient may occur not only in a simple pipeline, but also in the complicated network.

The maximum and minimum transient pressure heads often govern the transient design of the water distribution network. Different pipes in the network have different responses to the different water hammer events. The maximum and minimum transient pressure heads of Cobdogla irrigation network (concrete pipes) have been found by performing the simulation of all the water hammer events separately. This provided an envelope of maximum and minimum transient pressure for the Cobdogla system, as shown in Figure 4. It has been observed that the gap between the maximum and minimum transient pressure is quite large for most of the pipes, and also that not a single water hammer event (loading) can represent a critical transient loading for the design of the network. Thus a comprehensive analysis of hydraulic transients must be carried out to identified the critical water hammer loadings for the cost-effective selection of the water hammer control measures for the water distribution networks.

5 CONCLUSIONS

A computer model for water hammer simulation of water distribution systems has been developed and applied to investigation of transient behaviour of low head irrigation system. The transient model, based on the method of characteristics, has been integrated with a hydraulic solver EPANET and is able to perform the simulation of the steady and unsteady flow in the pipeline network with reservoirs, nodes, junctions, in-line valves, outlet valves and surge tanks.

A comprehensive analysis of the transient events has been carried out for Cobdogla irrigation system in South Australia. The simulation results obtained show that the different water hammer events create different levels of pressure surge in different pipes within the system. It indicates that water hammer events generate a severe transient pressure not only in a simple series pipeline, but also in the networks. An approach for evaluation of the transient events has been developed and is applied to the evaluation of the transient pressure surge by the water hammer event. This provides engineers with a method for identifying the critical water hammer events for the cost effective transient design of water distribution systems.

6. ACKNOWLEDGMENT

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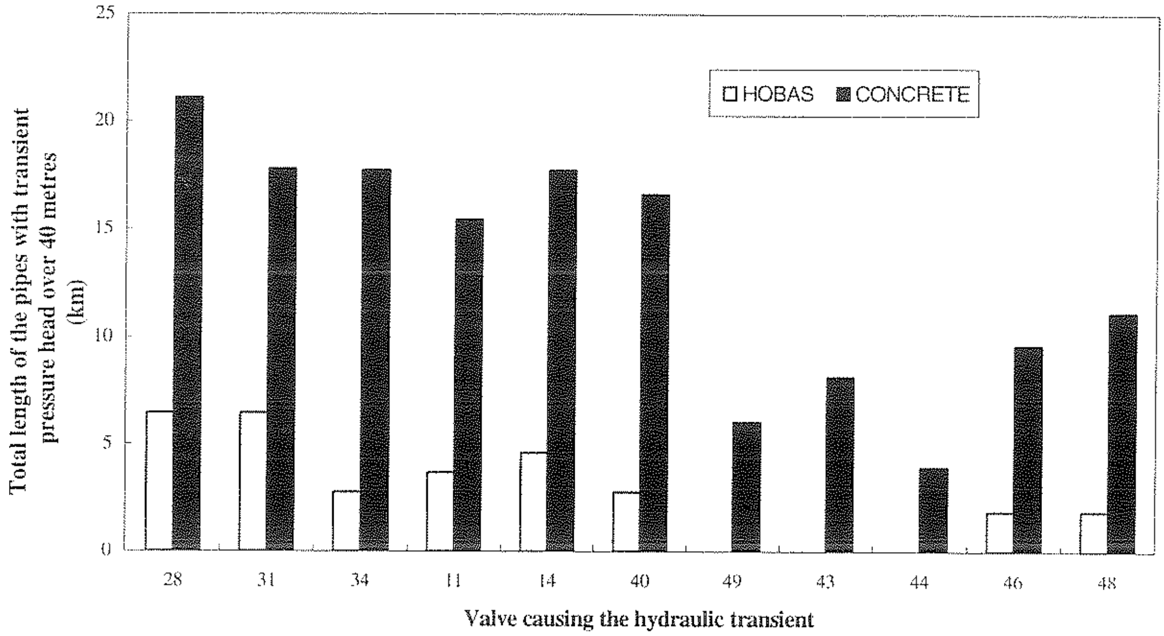

Figure 2 Evaluation of different transient events

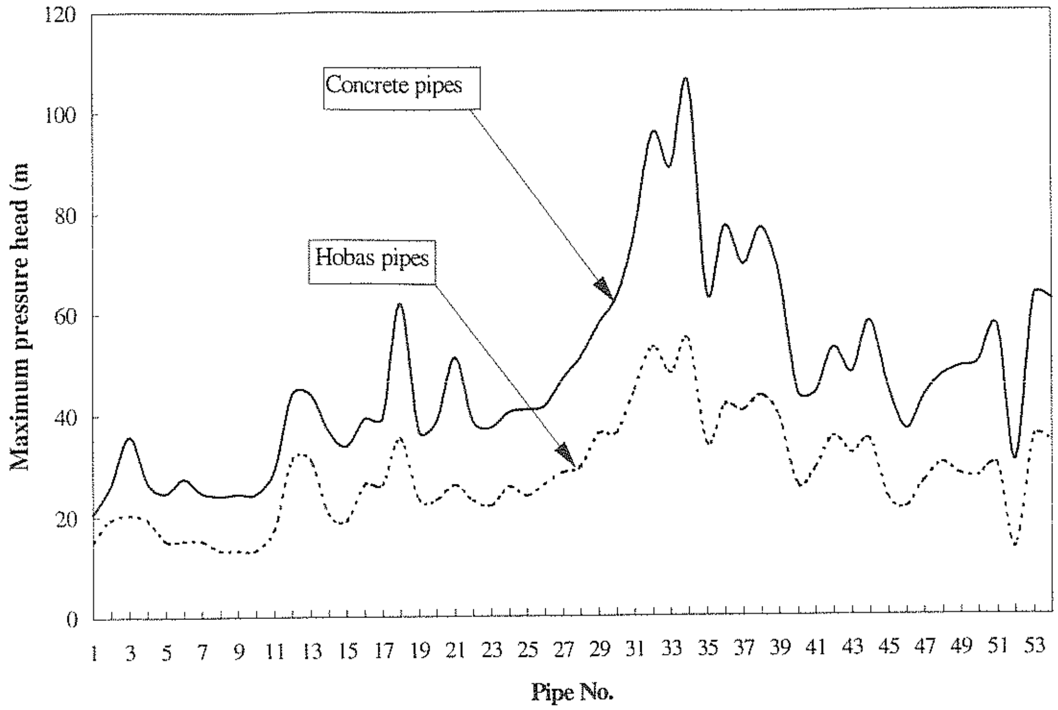

Figure 3 Comparison of maximum transient pressure by instantaneous closure of valve 28 for both concrete and Hobas pipes

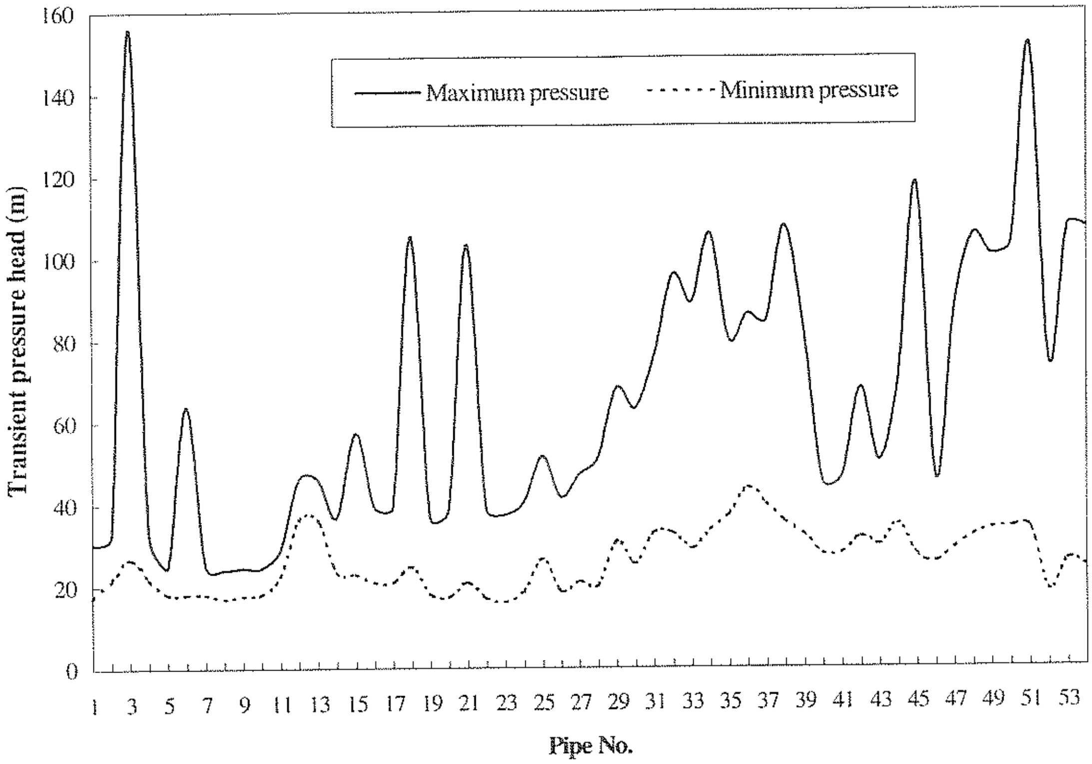

Figure 4 Transient pressure envelope of Cobdogla irrigation system by operating 11 valves