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Transient analysis for a pipe network

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ABSTRACT: In engineering practice, unsteady flow is of significant importance, which may cause excessive pressures, vibration, column separation, cavitation, and noise far beyond that caused by steady flow. In this paper, the method of characteristics is employed in transient analysis for a practical irrigation pipeline network. The simulation shows that the valve slamming may cause serious low pressure in the end of the main pipeline in about 10 seconds. Closing valve slowly or in a function of time may decrease the effect of transient loading and makes column separation occurring more later. But the transient also exists. Therefore, one-end surge tank or one-way surge tank are suggested to be adopted in this practical irrigation pipeline network.

1. INTRODUCTION

Transient problems are very important in irrigation engineering because of excessive pressures, cavitation and vibration caused in pipeline networks, which sometimes may cause the mechanics failure of pipe network. However, because early pipeline networks always were fed by gravity from high-elevation reservoirs or water towers and the number, length, diameter of pipes were typically small and pressures low, currently, most of the analyses in pipeline networks have been done only in the steady state, which usually leads to large errors because friction is not accurately known (Karney and Mcinnis, 1992). With the advances of science and technology, modern water distribution systems, by contrast, are usually fed by numerous pumping stations discharging directly into the system, flow disturbances are also common. For example, the adjustment of control valves, automatic stopping of pumps and influence of accidental events, such as power failure or fire demand, which all create unsteady flow or transient conditions. These disturbances make the transient analysis very significant for not only unsteady flow theory but also engineering practices.

Transient analysis in a practical pipeline network, which is mainly designed and projected for irrigation drainage near Fukuoka city of Japan, is introduced in this paper. Although some algebraic and conceptual frameworks have been investigated in many books and journals (Watters 1984; Wylie and Streeter, 1993; Ghidaoui and Karney, 1994), special attention is paid to the practical application of transient analysis in this study. No attempt is made to derive some new algorithm or to invent a new approach for unsteady analysis. Rather, the purpose is to show how the transient analysis method is used to engineering practice and solve a practical problem, thereby supply some useful suggestions or advises for the practical operational policies of the pipeline network.

2. MODEL FORMULATION

The analysis methods for unsteady flow in pipeline networks may be divided into two categories. One is the so-called rigid water column approach, in which the water is treated as inelastic substance. The other is the transient theory wherein the elasticity of both the water and the pipe walls is taken into account in the analysis. The transient theory more accurately reflects the behavior of the unsteady flow system. Although the analysis is more complex and difficult than the water column approach, with the assistance of high-speed computer the method of characteristics in transient approach can conveniently solve the equations in a easily understood manner. Combining with the features of the pipeline network studied, the method of characteristics is intended to apply in this study.

In pipeline networks, unsteady flow is generally described by two one-dimensional equations, i.e., the momentum equation and mass conservation equation

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{a^2}{gA}\dfrac{\partial Q}{\partial s} = 0 \\ \dfrac{\partial Q}{\partial t} + gA\dfrac{\partial h}{\partial s} + \dfrac{f|Q|Q}{2DA} = 0 \end{cases} \tag{1}$$

where h is head; a is wave speed; t is time; g is the acceleration due to gravity; D is inside diameter of pipe; Q is flow; A is area of the pipe; s is distance along the pipe; and f is Darcy-Weisbach friction factor.

The method of characteristics is a simple and numerically efficient method to solve above differential equations, which combines the momentum and mass conservation equations to form the following compatibility equations in velocity V and head H (Liggett and Chen, 1994),

$$\begin{cases} C^{+}: \dfrac{dV}{dt} + \dfrac{g}{a}\dfrac{dH}{dt} - \dfrac{g}{a}V\sin\alpha + \dfrac{f}{2D}V|V| = 0, & along\ \dfrac{ds}{dt} = V + a \\ C^{-}: \dfrac{dV}{dt} - \dfrac{g}{a}\dfrac{dH}{dt} + \dfrac{g}{a}V\sin\alpha + \dfrac{f}{2D}V|V| = 0, & along\ \dfrac{ds}{dt} = V - a \end{cases} \tag{2}$$

for the slope of pipeline which stands $dz/ds=\pm\sin\alpha$.

2.1 Initial conditions

In order to make transient analysis, initial conditions must be known beforehand. For a complex looped and branched system, this is not a trivial problem. In order to avoid spurious transients, it is usually best to obtain approximate values of heads and velocities from a steady state analysis. In analysis of steady flow in pipeline networks, two kind of approaches, i.e., node-approach and loop-approach, are usually employed. According to the features of pipeline network studied, as shown in figure 1, in which the number of branches is more than that of loops, the node-approach is adopted.

In the node-approach, the continuous equations of flow for each node are employed, which is characterized by its simple calculating. It is also named as energy-level approach, meaning that the relation between head loss and water level is used to establish basic equations. The basic equations of node-approach may be expressed as

$$\begin{cases} \sum_j Q_{ij} = -q_i - Q_{i0} \\ H_i - H_j = r_{ij}^{-\frac{1}{\alpha}}|Q_{ij}|^{(1/\alpha)-1}Q_{ij} + F_{Vij}|Q_{ij}|Q_{ij} \end{cases} \tag{3}$$

where Q_{ij} is flow discharged from node i to node j, which satisfies $Q_{ij}=-Q_{ji}$; Q_{i0} is flow discharged from node i to the outside of pipeline networks; q_i is flow taken from node i for water demand; H_i and H_j are water heads at node i and node j, respectively. In which,

$$\begin{cases} F_{Vij} = 8f_{Vij} \Big/ (g\pi^2 D_{ij}^{\ 4}) \\ r_{ij} = 0.27853 C_{ij} D_{ij}^{\ 2.63} L_{ij}^{\ -0.54} \end{cases} \tag{4}$$

where f_{vij} is loss coefficient of valve between node i and j; α is constant and equal to 0.54; C_{ij} is coefficient of flow velocity between node i and j; D_{ij} is inside diameter of pipeline between node i and node j; L_{ij} is length of pipeline between node i and j. According to analysis based on practical data of pipeline networks, following equations are established (Kawamura et al. 1989),

$$f_{Vij}(\theta) = \begin{cases} 165226 \times 10^{-0.180}, & 0 < \theta < 12.5 \\ 3696 \times 10^{-060}, & 12.5 \le \theta < 45 \\ 221 \times 10^{-0.030}, & 45 \le \theta \le 100 \end{cases} \tag{5}$$

where θ is the percent of valve opening. By using the Newton method, Q_{ij} and h_{ij} can be obtained. Then the initial conditions of unsteady flow are obtained.

2.2 Boundary Conditions

Boundary conditions usually consist of known pressures and sometimes of known velocities at boundary points in the pipeline network. According to the definition given by Karney and Mcinnis (1992), at the end of a pipeline, an auxiliary relation between head and velocity (discharge) need to be specified, this head-velocity relation is the so-called boundary condition. In this water distribution system, the following boundary conditions are defined.

The first kind is the internal boundary condition. In which the pipelines are connected each other with different diameters and also sometimes different material, therefore the velocity and wave speed are all different. The second kind of boundary condition widely occurs in this practical pipeline network, as shown in figure 1. In which the junction is with one in-flowing pipeline and two out-flowing pipelines. The third kind is the reservoir boundary condition, where the reservoir located at the end of utmost reach and supply water to the pipelines by gravity. At the section of utmost reach, the H-value remains constant for all calculation time. Of all the unsteady flow situations the engineers face and the most popular is from valve movement. Especially for the irrigation pipeline system, valves are widely used, which makes the flow to accelerate or decelerate depending on not only the mechanical design but also the movement procedures of the valve. If the valve in interior of a pipeline is programmed to close or open as some function of time, transient pressure may be decreased. The solution procedure follows closely the approach used for series pipes except the heads on each side of the valve are unequal. Equations are,

$$\begin{cases} C^{+}: V_{P1} = C_3 - C_4 H_{P1}, & \textit{along pipe } \mathbf{1} \\ C^{-}: V_{P2} = C_1 + C_2 H_{P2}, & \textit{along pipe } \mathbf{2} \\ V_{P1} = V_{P2} \\ H_{P1} = H_{P2} + K_L \dfrac{V_{P2}^{\ 2}}{2g} \end{cases} \tag{6}$$

Not to lose generality, a more complex situation is studied. As an example, a one-in, two-out, three-pipe junctions is analyzed. The equations are

$$\begin{cases} C^{+}: V_{P1} = C_1 - C_2 H_{P1u}, & \textit{along pipe } \mathbf{1} \\ C^{-}: V_{P2} = C_3 + C_4 H_{P2}, & \textit{along pipe } \mathbf{2} \\ C^{-}: V_{P3} = C_5 + C_6 H_{P3}, & \textit{along pipe } \mathbf{3} \\ V_{P1} A_1 = V_{P2} A_2 + V_{P3} A_3 + Q & \\ H_{P1d} = H_{P2} = H_{P3} = H_P & \\ H_{P1u} = H_{P1d} + K_L \dfrac{V_{P1}^{2}}{2g} & \end{cases} \tag{7}$$

where C_i (i=1~6) are parameters. Solving equation (7) by Newton-Raphson method, H_P, then V_{P1}, V_{P2}, V_{P3}, and H_{P1u} are not difficult to be obtained.

3. MODEL APPLICATIONS

In practical pipeline networks, whether irrigation drainage pipeline or water distribution pipeline of municipal water system, every kind of valves are widely used. The use of real valves in an unsteady flow situation has a substantial impact on pressures. This effect is more pronounced with great valves where the valve is always closed before it generates enough head loss to slow down the flow noticeably.

In this preliminary study, several situations which create transient are included mainly on the valve closing (opening) schedule. A linear valve closure over a closure time is analyzed. Which may be divided into, (1) valves are shut suddenly at the downstream of pipelines, this may happen when some accident occurs; (2) valve closure is in a function of time. For example, valve closes to 80% open in 10 seconds and closes the remaining amount in a total of 50 seconds from the beginning of valve movement. The information required to describe the system can be split into three types - node data, pipeline data, and boundary conditions data. Each type is characterized both by physical parameters and by an initial condition. The main data includes the pipeline length, diameter, valve velocity, friction factor, and elevation of node, etc.

In this study, the minimum number of reaches in the shortest pipeline is taken to be 3. From the pointview of convergence and stability, the maximum number of reaches in a long pipeline also must be kept not to be too large. Thus the number of reaches must actually be restricted to ensure reasonably accurate predictions of the maximum pressure can be obtained. Even so when the wave travel time in all pipelines is not a multiple of the wave travel time in the shortest pipeline, the need to interpolate is unavoidable. In this study, the linear interpolation in time or space is adopted. The steps of simulation in this study are: (1) to calculate basic parameters, e.g., f, D, α and wave speed a; (2) to calculate initial conditions based on steady flow analysis; (3) on the basis of initial and boundary conditions, unsteady flow analysis is proceeded to obtain H_P and V_P on the grid at time t; (4) step 3 is continued to "loop" until the time has reached T_{max} or negative pressure occurs. During this process the H and V value for each node or needed sections may be displayed on screen or drawn on plotter.

4. TRANSIENT ANALYSIS

With the combination of initial and boundary conditions calculated above, the steady flow analysis can be conducted, the energy line along the main pipeline is shown in figure 2, which also is the initial conditions of transient analysis. From steady flow analysis results the necessary inputs for transient analysis can be obtained.

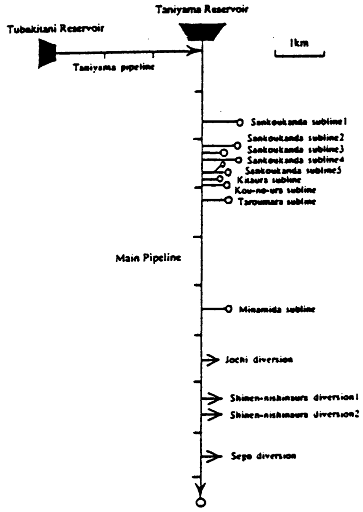

Fig.1 Pipeline network studied

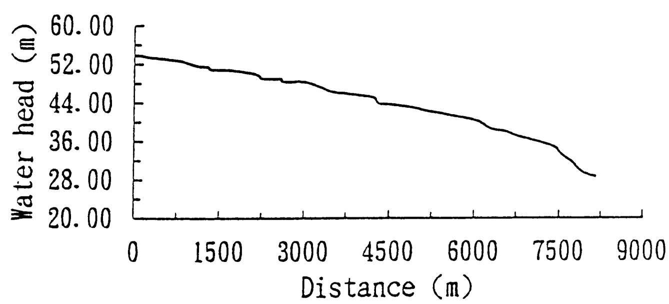

Fig.2 Distance-head relation in steady flow

For the simplest situation we assume that the valve installed in the utmost downstream of the main pipe, No.37 is closed suddenly because of accident. Then the column separation will occur at 11.295 second in pipe 36, where the minimum head attains -10.4 m, as shown in figure 3. The maximum head is 115.4 m, which also occurs in pipe 36 at 1.079 second just after the valve is shut down. Just before the column separation occurs the pressure line along the main pipeline is shown in figure 4.

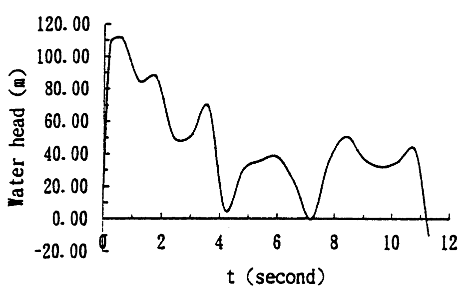

Fig.3 Time-head relation of pipe 36 in case 1

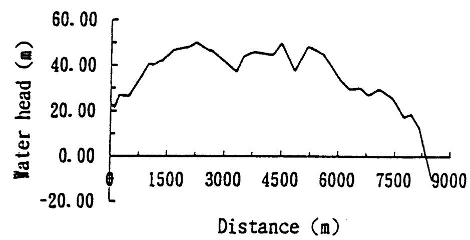

Fig.4 Distance-head relation in case 1

Then we further assume that the valves at sections 37 and 55, shut down simultaneously. Then the column separation occurs at 8.733 second in pipe 36, where the minimum head is -10.8 m. The maximum head in pipeline network also occurs in pipeline 36 at 3.429 seconds, which attains 156.9 m. The pressures at section 37 is shown in figure 5. The pressure changes along the main pipeline before the column separation occurs. Which is shown in figure 6.

As a more complex scenario, we assume that the valve at section 55 is closed suddenly, and the valve at section 37 closes to 10% open in 2 seconds and closes the remaining amount in a total of 50 seconds from the beginning of valve movement. Then the column separation will occur at about 10

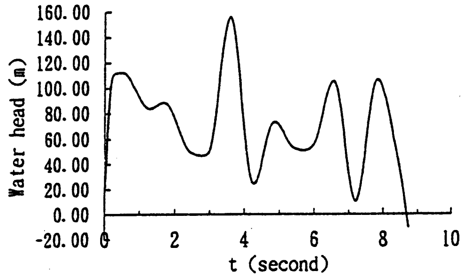

Fig.5 Time-head relation of pipe 36 in case 2

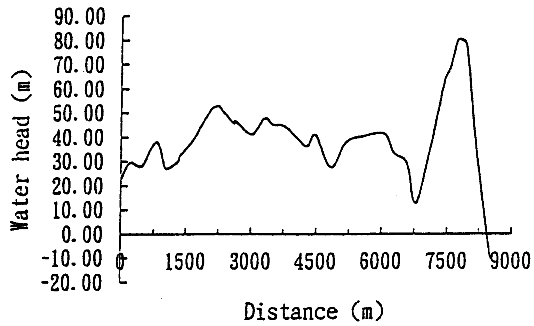

Fig.6 Distance-head relation in case 2

seconds in pipe 36, which is a little delaying for the coming of column separation compared with above situations. This preliminary results describe that closing valve in a reasonable schedule may decrease the effect of transient efficiently.

5. CONCLUSIONS

This study is in its preliminary step, where only two kind of situations in which valve closes suddenly or closes in a function of time , are investigated. It shows that closing the valve slowly and in a function of time may decrease the impact of high pressure or low pressure significantly. Especially the last 2~5 per cent or so of valve closure has the most critical effect for pipeline networks. Therefore, if possible it should be avoided to close valve suddenly as far as possible. However, there are many techniques and devices available which can be economically employed to prevent destructive effect from unsteady flow. For example, the one-end surge tank which is to both store or supply water rapidly and to act in controlling both high and low pressures in a pipeline, and one-way surge tank which is used to prevent low pressures, i.e., to prevent column separation, are suggested to be adopted in this practical irrigation pipeline network.

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