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Hydraulic Balance Adjustment Analysis and Optimization Method of Farmland Water Conservancy Pipe Network

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The hydraulic balance of farmland water conservancy pipe network is a common problem in the current large-scale farmland irrigation system. It is of great practical significance to study the different types of unsteady flow hydraulic calculations in farmland water pipe network for the safe and stable operation of farmland irrigation. In this paper, based on the characteristic's method, the mathematical model of the unsteady flow for farmland water pipe network was established, and the boundary conditions of the constructed model and the processing method for calculating the time step were given. Then, the proposed model was verified by actual examples, and the unsteady flow process of the irrigation pipe network was also calculated and analysed. The research results show that the method of characteristics can better optimize the boundary problem of water pump, nozzle and t-branch pipe in the unsteady flow of farmland irrigation pipe network. After the valve is closed, the water hammer pressure will appear in the irrigation pipe network system and propagate inside. The water hammer pressure at the valve is the largest; the greater the distance from the closing valve, the smaller the water hammer pressure. When closing multiple valves at the same time, complex water superimposing of hammer wave occurs in the pipe network, and the maximum water hammer pressure after superimposing is much larger than the single valve closing. The longer the valve is closed, the smaller the maximum head pressure at the same monitoring point. The research conclusion can provide a theoretical reference for the engineering treatment of the unsteady flow in the farmland water conservancy pipe network.

1. Introduction

Now, there exist water shortages, low water use efficiency, and low water productivity in agricultural irrigation water around the world (Panagopoulos and Makropoulos, 2014; Wang, Qiao and Chen, 2009; Lorite et al., 2007). It's the research focus in the field of farmland water conservancy to study agricultural high-efficient water-saving technology and improve water resource utilization.

Farmland water conveyance in pipe network is a farmland irrigation technology that has been vigorously promoted in recent years. It has the advantages of high-water resource utilization rate, simple construction and favourable promotion, and high degree of automation. However, there are also defects such as low-pressure capacity of the pipe network, large differences in water conveyance pressure, unsteady flow in the pipe network (Gad and Mohammed, 2014; Meng, Liu and Li, 2012). The unsteady flow of water conveyance in the pipeline network refers to the changes of the pressure and flow velocity of the entire pipe network due to the sudden change of the local water pressure or flow velocity of the conveying water; in severe cases, it can even cause the breakdown of the pipe network water conveyance system (Kumar et al., 2002; Man, Nishiyama and Anyoji, 2007; Li et al., 2015). Currently, the unsteady flow in the pipe network is a common problem in large-scale farmland irrigation systems. It is of great practical significance to study the different types of unsteady water flow calculations in farmland water pipe network for the safe and stable operation of farmland irrigation (Bergant, Simpson and Tijsseling, 2006; Fadaee and Tabatabaei, 2011; Lv et al., 2018; Tian et al., 2008). At present, the steady flow has been mostly studied in the existing researches on irrigation of farmland water conservancy pipe network. The hydraulic variation of the unsteady flow in the pipe network is extremely complicated, and the topological structure of the pipe network is difficult to be expressed in the unsteady flow modelling. Thus, there has been less research on the unsteady flow of the pipe network (Afshar

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and Rohani, 2008; Anwar, 2000). The research on unsteady flow of pipe network mostly focuses on the pipe network hydraulic calculation, computer modelling method of pipe network structure expression.
In this paper, based on the existing research and method of characteristics, the mathematical model of the unsteady flow for farmland water pipe network was established, and the boundary conditions of the constructed model and the processing method for calculating the time step were given. Then, the proposed model was verified by actual examples, and the unsteady flow process of the irrigation pipe network was also calculated and analysed. The research conclusion can provide a theoretical reference for the engineering treatment of the unsteady flow in the farmland water conservancy pipe network.

2. Farmland pipe network unsteady flow model and solution method

The motion control of the farmland pipe network system in any conveying section can be expressed as:

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\mathrm{g}\frac{\partial H}{\partial x}+\frac{fV|V|}{2D}=0 \tag{1}$$

The continuity equation is given as:

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}-V\sin\alpha+\frac{a^2}{\mathrm{g}}\frac{\partial V}{\partial x}=0 \tag{2}$$

where, V and t are respectively the water flow velocity and transportation time; f, D, and H are the friction coefficient, the diameter of the conveying pipe, and water head, and α is the pipe inclination. The characteristics method was used to combine formula 1 with 2.

$$L=L_1+\lambda_2 L_2=\left[\frac{\partial V}{\partial t}+\left(V+\frac{\lambda a^2}{\mathrm{g}}\right)\frac{\partial V}{\partial x}\right]+\lambda\left[\frac{\partial H}{\partial t}+\left(V+\frac{\mathrm{g}}{\lambda}\right)\frac{\partial H}{\partial x}\right]-\lambda V\sin\alpha+\frac{fV|V|}{2D}=0 \tag{3}$$

λ is the set unknown factor, let:

$$\frac{\mathrm{d}x}{\mathrm{d}t}=V+\frac{\lambda a^2}{\mathrm{g}}=V+\frac{\mathrm{g}}{\lambda} \tag{4}$$

Then λ can be converted to be:

$$\lambda=\pm\frac{\mathrm{g}}{a} \tag{5}$$

Substituting λ value into formula 3, the ordinary differential equation is derived as:

$$C^+:\begin{cases}\dfrac{\mathrm{d}x}{\mathrm{d}t}=a\\[2mm] \dfrac{\mathrm{d}H}{\mathrm{d}t}+\dfrac{a}{\mathrm{g}A}\dfrac{\mathrm{d}Q}{\mathrm{d}t}+\dfrac{faQ|Q|}{2\mathrm{g}DA^2}=0\end{cases} \tag{6}$$

$$C^-:\begin{cases}\dfrac{\mathrm{d}x}{\mathrm{d}t}=-a\\[2mm] \dfrac{\mathrm{d}H}{\mathrm{d}t}-\dfrac{a}{\mathrm{g}A}\dfrac{\mathrm{d}Q}{\mathrm{d}t}-\dfrac{faQ|Q|}{2\mathrm{g}DA^2}=0\end{cases} \tag{7}$$

A is the cross-sectional area of any conveying pipe within the pipe network.

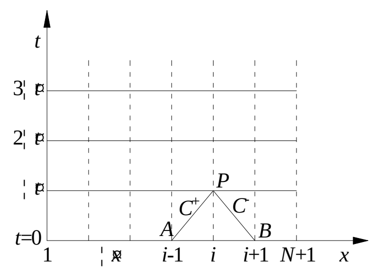
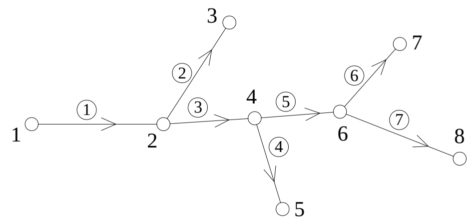


Figure 1: Characteristics network

Figure 1 shows the constructed rectangular characteristic network. Using the grid of Figure 1 to perform finite difference and discretization of ordinary differential equations, the compatibility equation is derived as:

$$\left(H_{\mathrm{P}}-H_{\mathrm{A}}\right)+\frac{a}{\mathrm{g}A}\left(Q_{\mathrm{P}}-Q_{\mathrm{A}}\right)+\frac{fQ_{\mathrm{A}}\left|Q_{\mathrm{A}}\right|}{2\mathrm{g}DA^{2}}\Delta x=0 \tag{8}$$

$$\left(H_{\mathrm{P}}-H_{\mathrm{B}}\right)-\frac{a}{\mathrm{g}A}\left(Q_{\mathrm{P}}-Q_{\mathrm{B}}\right)-\frac{fQ_{\mathrm{B}}\left|Q_{\mathrm{B}}\right|}{2\mathrm{g}DA^{2}}\Delta x=0 \tag{9}$$



where, a is the wave velocity of water hammer; Δx is the spacing between points A and B in Fig.1.

3. Farmland pipe network structure simplification processing and unsteady flow calculation process

In the actual irrigation operation of farmland, the structure of the pipe network system is very complicated. Since the researchers generally only focus on the water flow pressure and flow of each line in the farmland pipe network system, the pipe network system structure can be simplified, and the directed line graph of pipe network is utilized (Figure 2). In Figure 2, the arrows indicate the direction of water flow in the pipe network, the circle represents the intersection of pumps and pipelines etc., and the number represents the branch number of the pipe network.

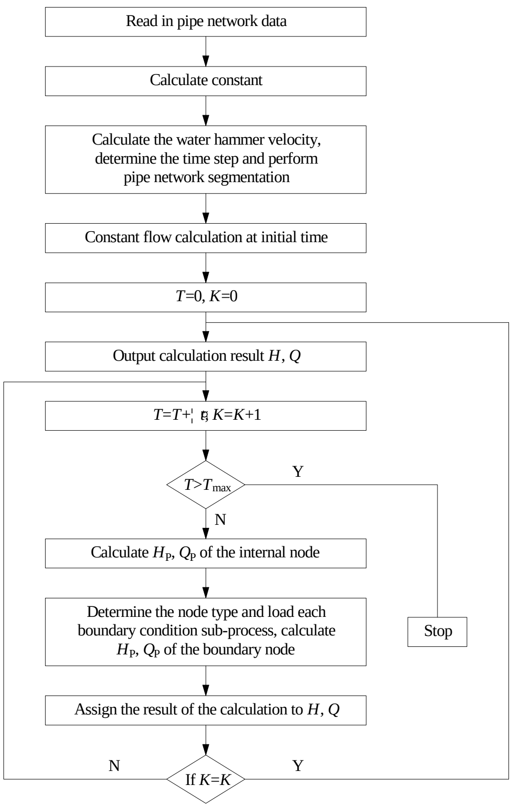


Figure 3: shows the calculation process of the unsteady flow in the farmland pipe network irrigation system. The main steps are as follows:

(1) Enter the basic data of the farmland pipe network irrigation system;
(2) Calculate parameters such as pipe characteristic coefficient, friction coefficient, water hammer wave velocity, time step length, etc.;
(3) Calculate the flow pressure and flow rate of all water pipes at the initial moment;
(4) Adjust the time step according to different situations, and sequentially determine the boundary conditions of each pipe node;
(5) Repeat the above steps until the calculation time length is greater than the pre-set maximum time length.

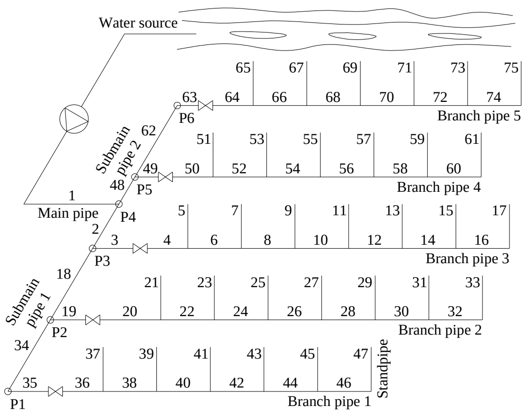


Figure 4: Farmland pipe network irrigation system layout

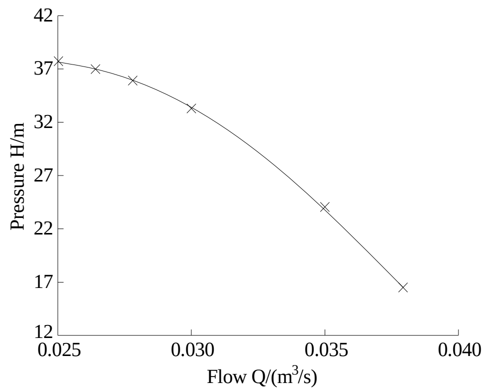


Figure 5: Curve of pump flow and pressure in farmland pipe network irrigation system

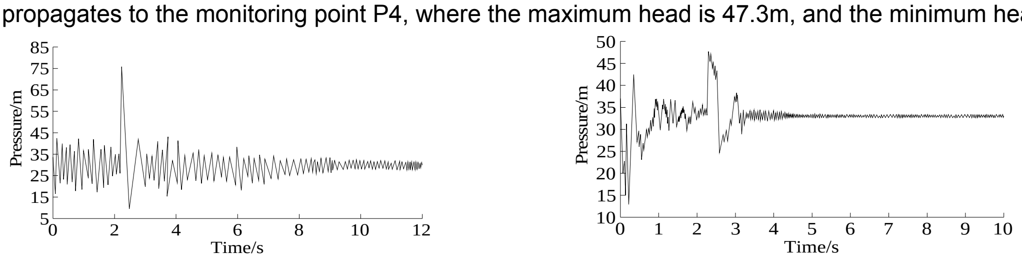
4. Example verification and analysis

The unsteady flow hydraulic calculation model proposed in this paper was verified by an actual farmland pipe network irrigation system. The pipe network layout is shown in Fig.4. The whole system consists of one total water pipe, six branch water pipes and 32 vertical pipes. The maximum pressure of the pipe wall is 1.25 MPa for the main water pipe and the branch water pipes, and the maximum pressure of the pipe wall is 1.0 MPa for the vertical pipe. The maximum spray range is 20m and the working pressure is 300kPa. Each branch water pipe is equipped with an independent working water pump with the pump power of 15KW. Fig.5 shows the relationship between the flow rate and pressure of the pump (Song and Li, 2018).

It's conducted in two cases. In the first case, the valve of the branch water pipe 1 was closed at the initial time for 2s, 5s and 8s respectively, and then the pressure fluctuation of the pipe network irrigation system was calculated; in the second case, the valves of the branch water pipe 1 and 2 were closed simultaneously, and after closing for 2s, 5s and 8s, respectively, the pressure fluctuations and head changes at different monitoring points were calculated.

Fig.6 shows the change of the water flow pressure at the monitoring point P1 and P4 after closing the valve of the branch water pipe 1 for 2s. Fig.7 shows the maximum water hammer pressure for the six monitoring points at different closing times.

It can be seen from Fig. 6 that when the valve of the branch water pipe 1 is closed, the water hammer wave is generated at the valve; at t=2s, the water hammer wave is transmitted to the monitoring point P1, where the maximum water head is 76.2 m, and the minimum water head is 10.9m; at t=2.2s, the water hammer wave propagates to the monitoring point P4, where the maximum head is 47.3m, and the minimum head is 13.5m.



(a) P1 pressure change *(b) P4 pressure change*

Figure 6: Pressure change of monitoring points P1 and P4 after closing the valve of branch water pipe 1 for 2s

It can be seen from Fig. 7 that the variation trend of the maximum pressure at the six monitoring points is basically the same under different valve closing times, that is, the pressure value of the monitoring point P1 is the maximum, the pressure value of the monitoring point P5 is the minimum, and the pressure value of the monitoring point P6 increases again. This is because the water hammer wave generated by the closing of the valve has a reflex phenomenon at P6, and the reflected wave and the backward waveform produce a superimposed effect. Besides, the longer the valve closing time, the smaller the maximum head pressure at the same monitoring point.

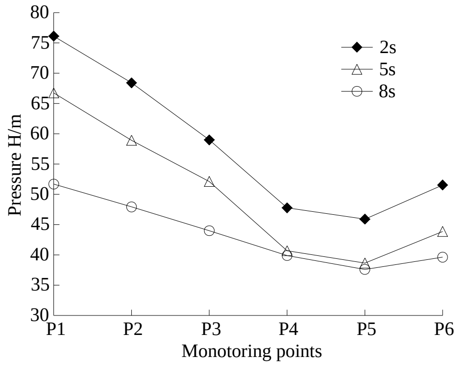
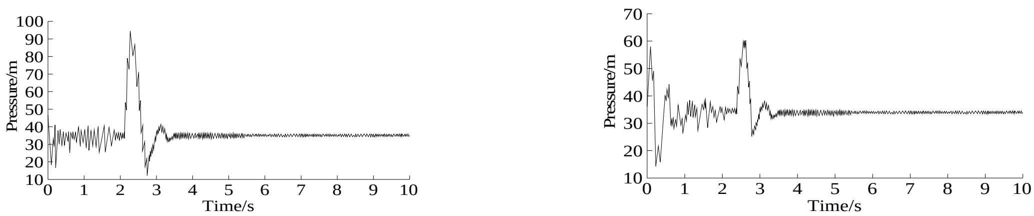
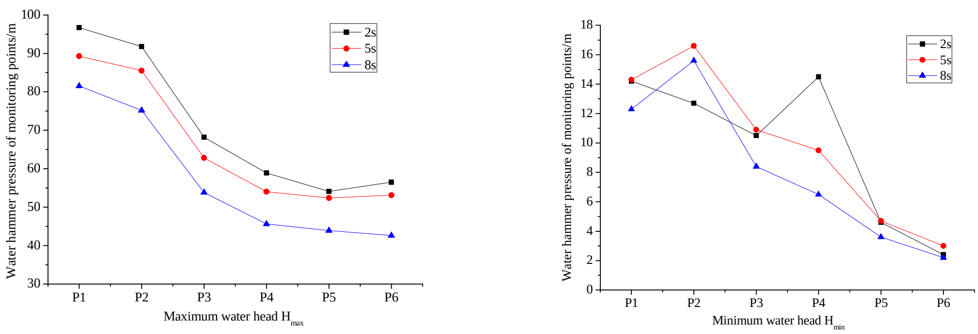


Figure 7: Maximum water hammer pressure of six monitoring points at different closing times.



(a) P2 pressure change *(b) P4 pressure change*

Figure 8: Pressure changes at monitoring points P2 and P4 after closing the valves of branch water pipes 1 and 2 for 2s.



(a) Maximum water hammer pressure *(b) Minimum water hammer pressure*

Figure 9: Maximum and minimum water hammer pressure of six monitoring points at different closing times

Fig.8 shows the pressure changes of the monitoring points P2, P4 after closing the valves of the branch water pipes 1 and 2 for 2s. It can be seen from the figure that when the two valves are closed at the same time, due to the complicated superimposing of the water hammer wave, the maximum head pressure generated is much larger than when the valve is closed; at P2, the maximum head is 92.1m, and the minimum head is 12.8m; at P4 the maximum head is 58.7m and the minimum head is 14.7m. Fig.9 shows the maximum and minimum water hammer pressures of the six monitoring points at different closing times. It can be seen from the figure that the variation tread of maximum and minimum water hammer pressures at the six-monitoring points change are basically the same under different closing times.

5. Conclusions

In this paper, based on the characteristic's method, the mathematical model of the unsteady flow for farmland water pipe network was established, and the boundary conditions of the constructed model and the processing method for calculating the time step were given. Then, the proposed model was verified by actual examples, and the unsteady flow process of the irrigation pipe network was also calculated and analysed. The research conclusions are as follows:

The characteristic line method can better optimize the boundary problem of water pump, nozzle and t-branch pipe in the unsteady flow of farmland irrigation pipe network.

After closing the valve, the water hammer pressure will appear in the irrigation pipe network system and propagate inside. The water hammer pressure at the valve is the largest; the greater the distance from the closing valve, the smaller the water hammer pressure. When closing multiple valves at the same time, complex water superposition of hammer wave occurs in the pipe network, and the maximum water hammer pressure after superimposing is much larger than when closing the single valve. The longer the valve is closed, the smaller the maximum head pressure at the same monitoring point.

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