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Robustness of water hammer protection of different formulas of frictional head loss

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ABSTRACT

The current widely used Darcy formula, Chezy formula, Hazen–Williams formula and other formulas of frictional head loss of hydraulic calculation are analyzed. Taking a long-distance water conveyance project as an example, the hydraulic model is established for numerical simulation. two-stage slow-closing valves, one-way surge tank, and pressure tank, the three water hammer protection scheme for a variety of formulas of frictional head loss, the robustness of which are studied, and then results of different formulas and different water hammer protection scheme are compared. The results showed that the pressure tanks with different formulas of frictional head loss both have effective water hammer protection. It indicated that the robustness of this scheme for different formulas of frictional head loss is the strongest, and the pressure tank is the proposed scheme for water hammer protection, to avoid the selection differences of formulas of frictional head loss affect water hammer protection.

Keywords: Frictional head loss; Hazen–Williams formula; Water hammer protection; Pressure tank; Robustness

1. Introduction

The main head loss of long-distance water transmission pipeline is a frictional head loss. At present, the formulas for calculating the frictional head loss along the pipeline mainly include Darcy formula, Chezy formula, and Hazen-Williams formula, and the calculation results of different formulas influence the pump selection and pipeline design. A study adopts Darcy formula and Hyzen-Williams formula to calculate the frictional head loss of PVC-U water pipe with different pipe diameters and flow rates, and the appropriate frictional head loss calculating formula under different pipe diameters and flow rates are obtained [1]. Point out the influence of different pipeline characteristic conditions on the hydraulic calculation results, and suggest that in the design of large diameter and long-distance water transmission pipeline, the Colebrook formula, which is applicable to three turbulent regions, should be adopted to replace the Hazen-Williams formula, to obtain relatively safe and reasonable design results [2]. Others discuss the applicable scope of the commonly used water head loss calculation formula and the selection of parameters in the formula and believe that the hydraulic calculation should adopt the corresponding calculation formula according to different flow patterns, and select the corresponding hydraulic calculation parameters, to make the hydraulic calculation results accurate and reliable [3,4]. Analyzing and comparing various calculation methods of pipeline frictional head loss determines the factors affecting frictional head loss and their influence degree on the frictional head loss [5,6]. Code for design of outdoor water supply (GB 50013--2006), according to the different pipe materials and the common range of flow rate, suggests selecting the formulas of water head loss of plastic pipe, concrete pipe and water distributing network.

The above research mainly analyzes the selection and the applicability of the frictional head loss formula. However, since there is no clear and detailed specification for the specific calculation formula for the water head loss of each type of pipeline, therefore the designers mainly choose the formula according to their own experience in the actual design process. It often occurs that in the same project, the design pressure of the pipeline is different because the designers use

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different calculation formulas. The steady-state simulation of water hammer protection is carried out according to the formula adopted by the designer. Therefore, different frictional head loss formulas will affect the hydraulic conditions of the pipeline, thus affecting the selection of a water hammer protection scheme. A water hammer protection scheme selected under one head loss formula may fail under another calculation formula. To ensure the safety of water supply and avoid the failure of a water hammer protection scheme caused by the improper selection of the calculation formula of frictional head loss. This paper takes a long-distance water transfer project in China as an example, establish a hydraulic model for numerical simulation, and through three water hammer protection schemes, that is, two-stage slow-closing control valve, one-way pressure regulating tower and air pressure tank, the applicability of various formulas for calculating frictional head loss is studied, then the calculation results of the same water hammer protection scheme with different formulas are compared.

2. Commonly used frictional head loss calculation formula

The hydraulic calculation of pipeline in water supply engineering generally follows the uniform flow calculation. At present, the formulas adopted in engineering design include Darcy formula, Chezy formula, and Hazen–Williams formula. Of which, Darcy formula, Chezy formula are both suitable for hydraulic calculation of pipelines and open channels. Hazen–Williams formula has less influence on parameters, as a traditional formula, it is widely used in the calculation of pipe network system at home and abroad. In the three hydraulic calculation formulas, the coefficients related to the roughness of pipeline inner wall are all important parameters affecting the calculation results [7–14].

2.1. Chezy formula

$$h_f = \frac{v^2}{c^2 R} l \tag{1}$$

In the Eq. (1): h_f – frictional head loss (m), v – the average velocity of cross-section (m/s), C – Chezy coefficient, R – hydraulic radius of cross-section (m), namely, cross-sectional area divides wetted perimeter, l – pipe canal length (m)

2.2. Darcy formula

$$h_f = \lambda \frac{l}{d} \frac{v^2}{2g} \tag{2}$$

In the Eq. (2): d – section diameter (m), g – gravitational acceleration (m/s^2), λ – resistance coefficient, $\lambda = 8g/C_2$.

2.3. Hazen–Williams formula

Hazen–Williams formula is applicable to the calculation of smooth circular pipe full of turbulence, which is mainly used for the hydraulic calculation of water supply pipeline. The Eq. (3) is:

$$h_f = \frac{10.67 \cdot Q^{1.852} l}{C_w^{\ 1.852} \cdot d^{4.87}} \tag{3}$$

In the formula: d – section diameter (m), Q – pipeline flux (m^3/s), C_w – resistance coefficient.

3. Water hammer protection calculation formula

3.1. Two-stage slow-closing control valve

$$\Delta H_{\text{valve}} = C_v Q_n^2 v|v| \tag{4}$$

$$C_v = \frac{\zeta}{2gA_v^2} \tag{5}$$

In the Eqs. (4) and (5): Q_n – a rated flow of the pump, m^3/s; v – the relative flow of the pump, $v = Q/Q_n$; C_v – valve resistance characteristic coefficient; ζ – hydraulic resistance coefficient of a valve at a certain closing angle θ; A_v – actual flow area at a certain closing angle θ_g, m^2.

For the closing angle θ, in valve two-stage closing butterfly process, set fast closing as t_1, and fast closing angle is ϕ_1; Set slow-closing as t_2 and slow closing angle is ϕ_2, then the closing angle at any time t is θ:

Fast closing stage $t \le t_1$, $\theta = \phi_1/t_1 \cdot t$.

Slow closing stage $t_1 < t < t_1 + t_2$, $\theta = \phi_1 + \phi_2 / t_2\,(t - t_1)$;

Closing complete $t \ge t_1 + t_2 = t_c$, $\theta = \phi_1 + \phi_2 = 90°$.

When $t \ge t_1 + t_2$, that is, after the butterfly valve is completely closed, $\theta = \phi_1 + \phi_2 = 90°$, the water pump flux or relative flow rate v are both zero.

There is a valve action at the pump outlet in the process of stopping the pump water hammer (such as butterfly valve two-stage closure), the head balance Eqs. (6) and (7) should be:

$$\begin{aligned} F_1 = \left(C_P - C_M\right) - 2BvQ_n + H_n\left(\beta^2 + v^2\right) \\ \left(A_0 + A_1 x\right) - C_v Q_n^2 v|v| = 0 \end{aligned} \tag{6}$$

$$\left(\beta^2 + v^2\right)\left(B_0 + B_1 x\right) + m_0 - \frac{GD^2}{g}\frac{N_n}{M_n}\frac{\pi}{60\Delta t}\left(\beta_0 - \beta\right) = 0 \tag{7}$$

Put Eqs. (6) and (7) together, working out v and β.

3.2. One-way surge tank

$$Q_{p1} + Q_{p3} = Q_{p2} \tag{8}$$

$$Q_{p2} = C_a A_p \sqrt{2g(H_{p3} - H_p)} \tag{9}$$

$$H_{p3} = S_{\max} + Z - \frac{Q_{p3} + Q_3}{2} \cdot \frac{\Delta t}{F} \tag{10}$$

when

$$H_{p3} \le H_p,\ Q_{p3} = 0 \tag{11}$$

$$Q_{p1} = \frac{(-H_p + C_{pt})}{B_1} \tag{12}$$

$$Q_{p2} = \frac{(H_p + C_{m2})}{B_2} \tag{13}$$

In the Eqs. (8)–(13), Q_{p1} – the flow in the pipe before flowing through the surge tank, m^3/s; Q_{p2} – the flow in the pipe after flowing through the surge tank, m^3/s; Q_{p3} – the flow outflow the surge tank, m^3/s; C_a – flow coefficient of surge tank outlet; A_p – the flow area of filling short pipe, m^2; H_{p3} – water level of surge tank, m; H_p – pipe pressure, m; $S_{\max}$ – Maximum water level controlled by float valve in surge tank (constant), m; Z – the height of the surge tank relative to the datum level, m; Q_3 – the flow in the surge tank, m^3/s; Δt – the outflux time of surge tank, s; F – the cross-sectional area of the surge tank, m^2;

3.3. Air pressure tank

As for air pressure tank, it can be assumed that the pressure is the same everywhere in the air chamber at any instant, and the inertia of the gas and the friction of the tank wall can be ignored, and the gas obeys a reversible and variable relationship:

$$pV^k = C \tag{14}$$

In the Eq.(14): p – the absolute pressure of the gas, Pa; V – volume of gas, m^3; k – Air state index; C – constant.

Flow continuity Eq. (15) of the bottom node of the air pressure tank is:

$$Q_{\text{in}} = Q + Q_s \tag{15}$$

In the formula: Q_{in} – pipe flows into the node, m^3/s; Q – pipe flow out of the node, m^3/s; Q_s – the flow into the pressure tank, m^3/s.

The resistance Eq. (16) of the throttle orifice of an air pressure tank is:

$$h_l = \sigma \frac{v^2}{2g} \tag{16}$$

In the equation, σ – throttle orifice resistance coefficient; v – the flow rate through the throttle orifice; m/s g – gravitational acceleration, m/s^2.

Pressure Eq. (17) at the bottom of the air pressure tank is:

$$h_p = \left(\frac{p}{\gamma - h_b}\right) + h_s + z + h_l \tag{17}$$

In the equation, γ – the unit weight of water, N/m^3; h_b – Standard atmospheric head, m; h_s – water level in air pressure tank, m. z – the geometric height of the pipe where the air pressure tank is installed, m.

4. Water hammer protection scheme simulation

At present, there are three main water hammer protection schemes [15–20]: (1) Use air valves and pump outlet to shutoff valves for water hammer protection, generally, it is applicable to the pipeline which the fluctuation is not severe and water hammer harm is not serious. When there is serious water hammer negative pressure, it is difficult to alleviate. (2) The one-way surge tank is used for water hammer protection, which is suitable for areas that do not need anti-freezing and where land acquisition is not difficult. (3) Air pressure tank is installed in the pump station for water hammer protection, and it is suitable for a project in which the pipeline is undulating and water hammer negative pressure is serious. One-way surge tank and air pressure tank should not be used alone; otherwise, it will increase the burden of protection, thus increasing the equipment cost. Generally, water hammer protection should be carried out with a pipeline air valve and pump outlet shutoff valve.

To study the applicability of different water hammer protection schemes to different frictional head loss formulas, based on the data of a long-distance water conveyance project, a hydraulic model is established and three water hammer protection schemes are designed:

Scheme 1: air valve + two-stage slow-closing control valve;

Scheme 2: air valve + two-stage slow-closing control valve + one-way surge tank;

Scheme 3: air valve + two-stage slow-closing control valve + air pressure tank.

5. Comparative study on quasi-static calculation methods

5.1. Calculation model and parameter

In this paper, a long-distance water transfer project in China is taken as the research object for numerical simulation. Fig. 1 is the pipeline route profile. The water supply of the project is 5,600 m^3/h, DN1200 single line operation. The water source is equipped with three pumps, two in use and one standby, single pump flow is 2,800 m^3/h, and the design head is 24 m. The line is equipped with 10 DN150 air valves. On the basis of Scheme 1◎Scheme 2 set up one-way surge tank at 2,000 m of the pipeline. The designed water level is 63 m, and the height of surge tank is 5 m,

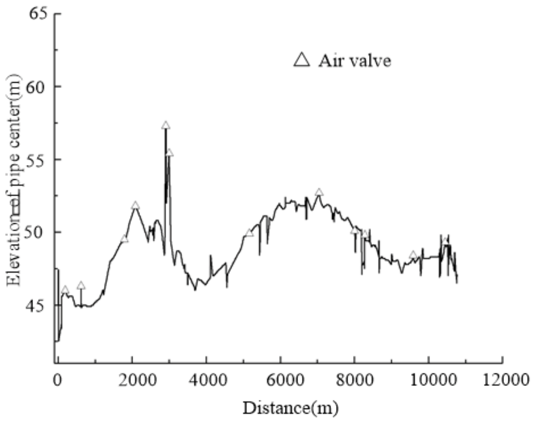
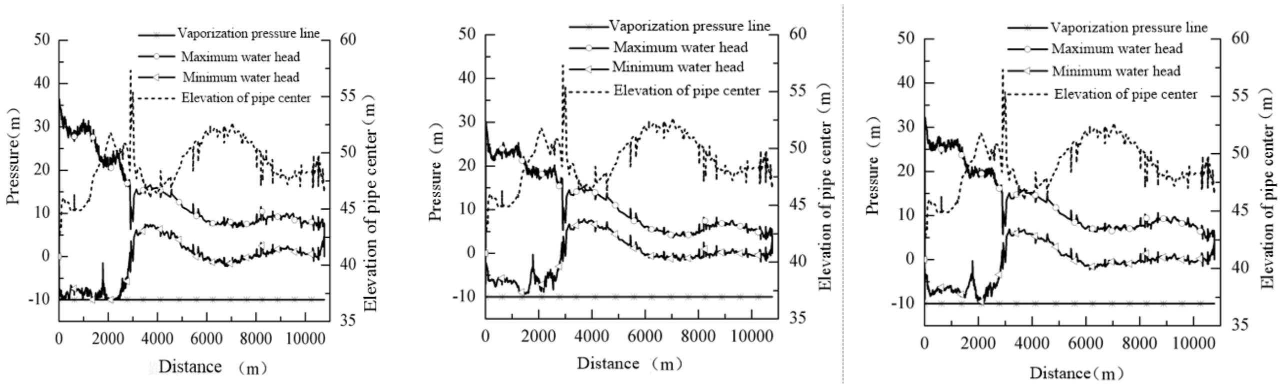


Fig. 1. Pipeline route profile.

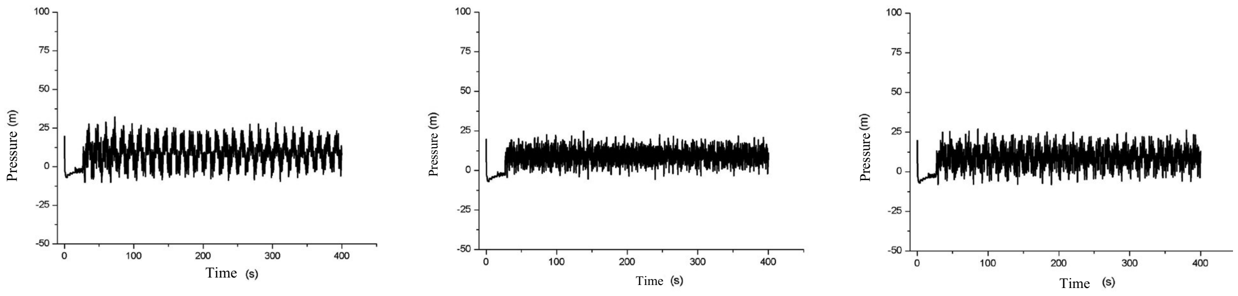


(a) Darcy formula--water hammer pressure envelope

(b) Hytzen-Williams formula--water hammer pressure envelope

(c) Chezy formula--water hammer pressure envelope

Fig. 2. Pressure envelope of water hammer protection scheme 1 in different frictional head loss formulas.



(a) Darcy formula--inlet pressure of pump stop in accident

(b) Hayzen-Williams formula-- inlet pressure of pump stops in accident

(c) Chezy formula -- inlet pressure of pump stops in accident

Fig. 3. Inlet pressure of water hammer protection scheme 1 in different frictional head loss formulas.

and the diameter is 4 m. The calculation results of water hammer protection are shown in Figs. 2 and 3.

5.2. Water hammer protection simulation of pump stop in an accident

This paper adopts Darcy formula, Chezy formula, Hazen–Williams formula as a formula for calculating frictional head loss in hydraulic model construction, and through the above three water hammer protection schemes, water hammer simulation of pump stopping accident is carried out, and then the robustness of the water hammer protection scheme under different frictional head loss is compared and analyzed.

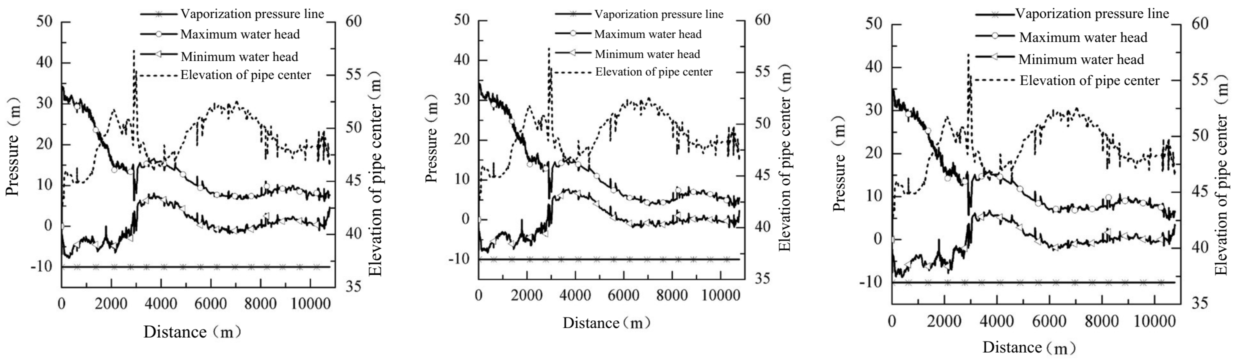
5.3. Water hammer calculation result comparison in scheme 3

Based on scheme 1, a 6 m^3 air pressure tank is set at the outlet main pipe of the water pump in scheme 3. The calculation results of the water hammer are shown in Figs. 4 and 5.

The analysis shows that when adopting the Darcy formula and Chezy formula and Hayzen–Williams formula to calculate in scheme 3, the negative pressure of the whole line is around –5 m, and the water hammer protection effect is the best, which meets the calculation requirements of water hammer protection. Comparing the results of water hammer protection under the three formulas, it can be concluded that Scheme 3 (air valve + two-stage slow-closing control valve + air pressure tank) has a very good water hammer protection effect under the three formulas, and its robustness is best. Compared with scheme 1 and scheme 2, the pressure fluctuation of the pump outlet valve is significantly alleviated after the pump stopping in an accident in scheme 3, indicating that the air pressure tank can stabilize the pump outlet pressure and alleviate the negative pressure problem of water hammer near the pump.

6. Conclusions

In this paper, through numerical simulation, three hydraulic models are established with Darcy formula, Chezy

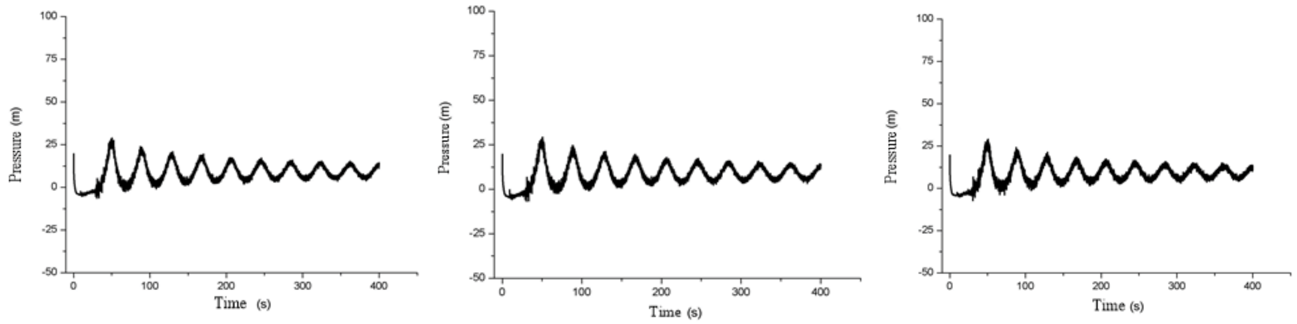


(a) Darcy formula--water hammer pressure envelope

(b) Hytzen-Williams formula--water hammer pressure envelope

(c) Chezy formula--water hammer pressure envelope

Fig. 4. Pressure envelope of water hammer protection scheme 3 in different frictional head loss formulas.



(a) Darcy formula--inlet pressure of pump stop in accident

(b) Hytzen-Williams formula--water hammer pressure envelope

(c) Chezy formula--water hammer pressure envelope

Fig. 5. Inlet pressure of water hammer protection scheme 3 in different frictional head loss formulas.

formula and Hazen–Williams formula as frictional head loss computational formulas, and three water hammer protection schemes are simulated in each model. The water hammer protection effects of each scheme are compared, and the following conclusions are obtained:

- Under the same water hammer protection scheme, when using Hazen–Williams formula to calculate, the effect of water hammer protection is better than that of Darcy formula and Chezy formula.
- Under the calculation of different frictional head loss formula, when using the air pressure tank, water hammer protection effect is the best, and robustness is also the best, relieving the pump outlet pressure obviously

When considering the influence of Darcy formula, Hytzen–Williams formula and Chezy formula on different water hammer protection schemes comprehensively, it can be found that in the design of water hammer protection scheme, we should not only consider the water hammer protection effect under a certain hydraulic condition but also consider the robustness of water hammer protection scheme comprehensively, to avoid the failure of water hammer protection caused by the difference in selecting frictional head loss formulas. Compared with the common water hammer protection scheme, setting the air pressure tank at the pump outlet has the best water hammer protection effect and the robustness is the strongest, which can be used as the preferred water hammer protection scheme.

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