Study on impedance size optimization of a one-way surge tank in a long-distance water supply system

Xuyun Chen, Jian Zhang, Xiaodong Yu, Sheng Chen and Lin Shi

ABSTRACT

The size of the impedance hole of the one-way surge tank will affect its protection against water hammer. In this paper, a mathematical model of one-way surge tank with impedance is established based on the characteristic line method. The pressure-reducing penetration formula of the one-way surge tank including impedance loss and the calculation formula of make-up water flow are deduced. Based on these formulas, the influence of impedance hole diameter ratio (ratio of impedance hole of one-way surge tank to diameter of water pipeline) on the water hammer protection effect is analyzed, and the reasonable value range of impedance hole diameter ratio is given. The correctness of the theoretical analysis results is verified by an engineering example. The results show that the pressure and flow relationship derived from the formula are consistent with the numerical simulation results. The penetration pressure drop of the one-way surge tank is inversely proportional to the impedance size. When the impedance hole diameter ratio is less than 0.2, the penetration pressure drop will cause serious negative pressure. The make-up water flow is proportional to the size of the impedance hole, and the make-up water volume should be reduced while ensuring that the pipeline has no negative pressure.

Key words | impedance hole, long-distance water supply project, one-way surge tank, pump stop, water hammer protection

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HIGHLIGHTS

- The mathematical model of impedance type one-way tower is established.
- The relationship between the penetration pressure drop of the tower and the size of the impedance hole is deduced.
- The relationship between the filling water flow rate of the tower and the size of the impedance hole is deduced.
- The reasonable value range of impedance hole size of the tower is given.

INTRODUCTION

Long-distance water supply projects can redistribute water resources and improve the utilization rate of water resources. In order to overcome the influence of topography, most long-distance water supply projects need to transfer water from low terrain to high terrain by means of pumping station pressurization (Ren *et al.* 2019).

When the water pump is suddenly cut off, the pressure after the pump drops sharply, and the pressure drop wave is quickly transmitted downstream. Where the initial internal pressure is small, the pipeline pressure may drop to the vaporization pressure, and liquid column separation occurs, which in turn induces the bridging of water

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hammer. The huge pressure generated by bridging the water hammer may cause severe damage to the entire water supply system, leading to the interruption of water supply and heavy losses (Besharat *et al.* 2015). Therefore, it is necessary to study the water hammer protection measures of the pumping station water supply system.

The current protection methods used to solve the pump-failure water hammer include air tanks, surge tanks, one-way surge tanks, air valves, etc. Compared with other protection measures, the one-way surge tank has the advantages of low cost, no terrain restriction, and can effectively protect negative water hammer, so it is widely used in engineering. Bergant *et al.* (1991) introduced the one-way surge tank as a water hammer control device, studied the protection performance of the one-way surge tank, and considered that it can effectively control the surge in the system. Stephenson (2002) proposed that a one-way surge tank can be used for negative pressure protection in low-head pipelines. Liu *et al.* (2002) put forward the protection scheme of using a one-way surge tank to prevent water column separation, and verified the rationality of the scheme through experiments. According to different parameters of one-way surge tank, Wang *et al.* (2006) analyzed the influence of its volume and initial water level on the hydraulic transient process of pumping accidents. Liu *et al.* (2008) analyzed the main factors affecting the water hammer protection effect of the one-way surge tank. Xu & Zhang (2009) proposed to arrange a one-way surge tank at the high point of the pipeline, which can not only effectively protect the pipeline from negative pressure, but also reduce the height of the one-way surge tank and save investment. Zhang *et al.* (2011) conducted an in-depth analysis on the installation principle and location of one-way surge tanks in long-distance water delivery projects. Zhou *et al.* (2015) found that setting a one-way surge tank in the urban pressurized water supply system could solve the possible water hammer problem.

Most of the above-mentioned studies on one-way surge tanks have focused on how to set up the scheme of one-way surge tanks and the impact of changes in the volume parameters of the one-way surge tank on the protection effect of water hammer, and rarely consider the impact of impedance on the protection effect of the one-way surge tank. However, in the actual operation of the water supply system, the influence of impedance cannot be ignored.

Wylie *et al.* (1993) discussed the influence of hydraulic impedance on hydraulic vibration, and proposed a calculation method for hydraulic impedance of a simple surge tank. Feng & Yang (2011) derived a formula for calculating the hydraulic impedance of an impedance surge tank. The study found that the greater the hydraulic resistance coefficient of the surge tank, the smaller the attenuation coefficient of the system. De Martino & Fontana (2012) proposed a new method for measuring the air chamber and impedance resistance, which simplified the method for determining the size of the impedance surge tank. Tong *et al.* (2018) studied the reasonable value of the ratio of the impedance hole area to the pressure channel section area of the impedance-type surge chamber for the diversion system of a specific hydropower station. Ye & Ju (2020) used the unsteady flow numerical simulation method to verify the minimum value of impedance hole area in the surge chamber of a hydropower station.

The selection of impedance hole size of one-way surge tanks is mostly based on numerical simulation or engineering experience, which has a certain degree of blindness. In order to simplify the design process of the impedance hole size, this paper establishes the mathematical model of the impedance one-way surge tank based on the characteristic line method, analyzes the relationship between impedance hole size of one-way surge tanks and pressure drop after pump and make-up water flow rate, and introduces the selection principle and specific range of impedance hole of one-way surge tanks, which can provide a reference for designers to quickly determine the size of impedance hole. At the same time, the method is verified by studying the actual cases introduced in this paper.

MATHEMATICAL MODEL

Figure 1 is a schematic diagram of an impedance-type one-way surge tank. Assuming that the boundary nodes of the

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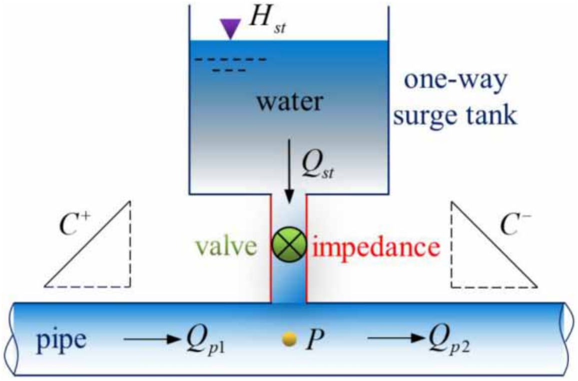

Figure 1 | Schematic of impedance one-way surge tank.

water inlet and outlet pipes are numbered 1 and 2, the control equation of the one-way surge tank is:
Flow continuity equation:

$$Q_{p2} = Q_{st} + Q_{p1} \tag{1}$$

Water head balance equation:

$$H_p = H_{st} - aQ_{st}|Q_{st}| \tag{2}$$

Relationship between flow rate and water level:

$$\mathrm{d}H_{st}/\mathrm{d}t = -Q_{st}/A_{st} \tag{3}$$

Compatibility equation of pressure pipeline:

$$\begin{aligned} H_p &= C_{p1} - B_{p1}Q_{p1} \\ H_p &= C_{M2} + B_{M2}Q_{p2} \end{aligned} \tag{4}$$

where H_{st} is the water level of the one-way surge tank (m); A_{st} is the cross-sectional area of the one-way surge tank (m^2); Q_{st} is the flow rate from the impedance hole of the one-way surge tank (positive when flowing out; m^3/s); a is the impedance head loss coefficient; H_p is the transient water head at the pipeline boundary (m); and Q_{p1} and Q_{p2} are the transient flow at the boundary of the pipeline (m^3/s).

SELECTION OF IMPEDANCE HOLE SIZE

The head loss value of the impedance hole of the one-way surge tank can be calculated by Equations (5) and (6).

$$\alpha = \frac{1}{2g\eta^4 A^2 \varphi} \tag{5}$$

$$H_\omega = \frac{Q_{st}^2}{2g\eta^4 A^2 \varphi} = \alpha Q_{st}^2 \tag{6}$$

where g is the acceleration due to gravity (m/s^2); A is the pipeline area (m^2); η is the ratio of the impedance hole diameter to the pipe diameter; φ is the flow coefficient; and H_ω is the head loss through the impedance hole of the one-way surge tank (m).

It can be seen from Equations (5) and (6) that the impedance loss of a one-way surge tank is mainly determined by the size of the impedance hole and the make-up water flow. When the pump is out of power, the larger the impedance hole size, the smaller the head loss. A strong capacity of the one-way surge tank to replenish water to the pipeline allows the pressure drop behind the pump and along the pipeline to be better controlled. If the impedance hole is too small, the head loss of the water flowing through the impedance hole is too large, which will lead to too little pressure through the one-way surge tank and it is easy to generate negative pressure. On the other hand, if the water in the one-way surge tank has difficulty flowing into the pipeline, the insufficient water supply capacity will lead to the failure of effectively protecting the pressure drop behind the pump. However, when the impedance hole size of the one-way surge tank is too large, the ability of water flowing out of the one-way surge tank is enhanced. This increases the water-level drop speed of the one-way surge tank, and the one-way surge tank makes up too much water to the pipeline, causing the minimum pressure at the bottom of the one-way surge tank to decrease, or even leak out.

From the above analysis, it can be seen that the size of the impedance hole in one-way surge tanks is affected by many factors, such as water hammer pressure, system pressure, height of one-way surge tank, area of one-way surge tank, etc. Therefore, it is necessary to consider the size of impedance holes of one-way surge tanks. The following two conditions should be met when selecting the impedance hole size:

1. The minimum impedance hole of the one-way surge tank should ensure that the pipeline under the influence of water hammer pressure drop does not have negative pressure.
2. The maximum impedance hole of the one-way surge tank should meet the pressure of the pump station system after the valve is quickly closed behind the pump, and the

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water depth of the one-way surge tank is within a safe range, that is, there is no negative pressure in the pipeline in front of the one-way surge tank and no leakage phenomenon.

Relationship between impedance hole size and penetration pressure drop

Since the minimum value of the impedance hole of the one-way surge tanks should ensure that the pipeline affected by water hammer depressurization does not show negative pressure, then it is first necessary to ensure that the pressure drop through the one-way surge tank should not be too large. Figure 2 shows the step-down diagram of the one-way surge tank under the condition of instantaneous pressure drop, where H_{st} is the water level elevation of one-way surge tank (m) and H_0 is the piezometric head during stable operation (m).

Since the pressure drop wave transmitted to this place is an instantaneous pressure drop, the pressure drop relationship can be approximately calculated according to the direct water hammer calculation formula, and the two satisfy the relationship:

$$\Delta H_A = \frac{a}{gA}(Q_0 - Q_{p1}) \tag{7}$$

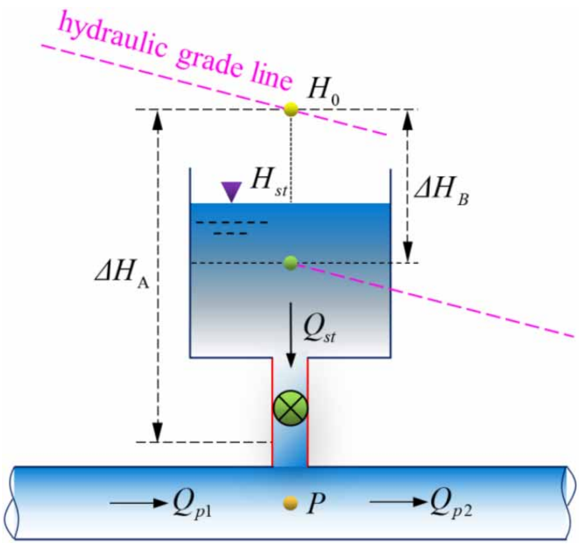

Figure 2 | Schematic of the pressure drop process of one-way surge tank.

where Q_0 is the flow rate during stable operation (m^3/s); ΔH_A is the pressure drop value transmitted to the one-way surge tank (m); and Q_{p1} is the flow rate when the pressure is reduced to the one-way surge tank (m^3/s).

Due to the existence of the one-way surge tank, part of the pressure drop wave is reflected by the one-way surge tank as a positive pressure wave and propagates to the front of the one-way surge tank, and part of it penetrates the one-way surge tank and continues to propagate to the pipeline behind the one-way surge tank. In the instantaneous depressurization process, the forward reflected positive pressure wave and backward propagating negative pressure wave can be approximately calculated using a direct water hammer formula, which satisfies the relationship:

$$\Delta H_B = \frac{a}{gA}(Q_0 - Q_{p2}) \tag{8}$$

$$\Delta H_A - \Delta H_B = \frac{a}{gA}(Q_{p2} - Q_{p1}) \tag{9}$$

$$Q_{p2} = Q_{p1} + Q_{st} \tag{10}$$

where ΔH_B is the pressure drop value that penetrates the one-way surge tank (m); Q_{p2} is the flow behind the one-way surge tank (m^3/s); and Q_{st} is the make-up water flow from the one-way surge tank to the pipeline (m^3/s).

It can be obtained by simultaneous Equations (6)–(10):

$$\Delta H_B = \frac{a^2 + 2aQ_0Ag\alpha - a\sqrt{a^2 - 4A^2g^2H_0\alpha + 4A^2g^2H_{st}\alpha + 4aQ_0Ag\alpha}}{2A^2g^2\alpha} \tag{11}$$

Using the Taylor expansion gives the first-order approximation:

$$\Delta H_B = H_0 - H_{st} + \frac{\alpha(AgH_{st} + aQ_0 - AgH_0)^2}{a^2} \tag{12}$$

The meaning of the third term on the right side of Equation (12) is the pressure drop loss caused by impedance, $\delta = \dfrac{\Delta H_A - \Delta H_B}{\Delta H_C}$ is defined as impedance loss ratio,

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its value is:

$$\delta = \frac{a\eta^2\varphi\sqrt{8g\Delta H_C + a^2\eta^4\varphi^2} - a^2\eta^4\varphi^2}{4g\Delta H_C} \tag{13}$$

where $\Delta H_C = \Delta H_A - (H_0 - H_{st})$.

If the flow coefficient is 1, the relationship between impedance loss ratio δ and diameter ratio η under different pressure drop differences, as shown in Figure 3.

It can be seen from Figure 3 that when the diameter ratio of impedance hole of the one-way surge tank is less than 0.2, the pressure drop loss ratio of the one-way surge tank will increase sharply, and when the diameter ratio is 0.1, it will increase to more than 1.5 times, which means the protection effect of the one-way surge tank is reduced by more than half. When the diameter ratio is 0.3 or above, the pressure drop loss of the one-way surge tank is not very different. Therefore, it is suggested that the diameter of the impedance hole of the one-way surge tank should be at least greater than 0.2 times the pipe diameter.

Relationship between impedance hole size and make-up water flow

When a power failure occurs to the pump, the pump head drops instantaneously, and when the negative pressure water hammer wave is transmitted to the one-way surge tank, the one-way surge tank begins to replenish water. According to the direct water hammer formula, the water supplement volume of the one-way surge tank in the prime minister process is:

$$V = \frac{2gAL_1}{a^2}(\Delta H_A + H_\omega) \tag{14}$$

where L_1 is the distance from the one-way surge tank to the downstream outlet pool (m).

Equation (14) does not take into account the drop in the water level during the replenishment process of the one-way surge tank. This calculation is only the effective replenishment volume of the one-way surge tank during the main process. Since the water body in the one-way surge tank has inertia, when the size of the impedance hole is large, the water body inertia is too large, which causes excessive water supply. This causes the pressure at the bottom of the one-way surge tank to be too low, which is not conducive to the protection of water hammer in the pipeline.

The actual make-up water volume of the one-way surge tank can be used as follows:

$$V = A \times \Delta H = A(\Delta H_B - H_{st}) \tag{15}$$

where ΔH is the drop height of the one-way surge tank water level (m).

The impedance diameter ratio of the one-way surge tank also has an upper limit due to the influence of make-up water speed. The minimum size of the impedance hole can be determined according to the first wave of pressure drop after the pump, but the influence on the water supplement speed is related to the situation of the entire pipeline. Numerical simulation can be used to determine the pressure change of the entire pipeline. In order to avoid excessive water supply, the size of impedance hole should not be too large.

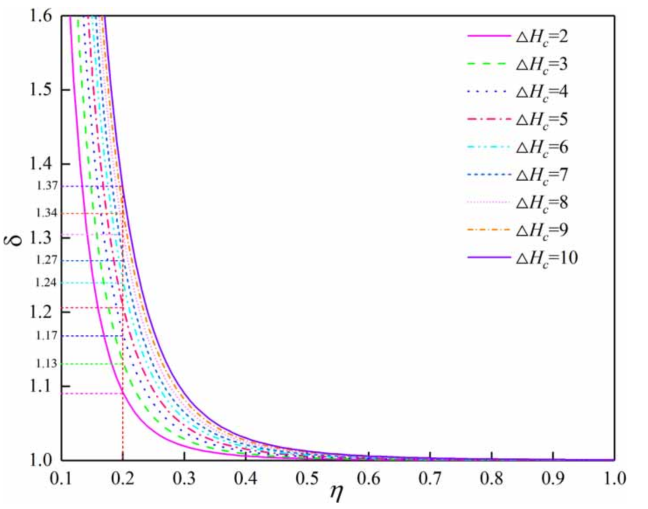

Figure 3 | The relationship between the loss ratio and the impedance hole diameter ratio under different pressure drop differences.

CASE STUDY AND ANALYSIS

In the water supply system of a pump station, the piping system adopts a single pipe arrangement, and its designed

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flow rate is 1.0 m^3/s. The water pipe-line uses a steel pipe with a diameter of 1.0 m, the water hammer wave velocity is about 1,000 m/s, and the pipe length is 8,495.0 m. A single pump is used for water pumping, the speed of the pump is 24.7 Hz, the corresponding motor power is 560 kW, and the maximum head is 25.0 m. The pipeline layout of the water supply system is shown in Figure 4.

Without protection

When the water pump is powered off, the pressure behind the pump drops rapidly. If there is no water hammer protection measures in the pipeline behind the pump, serious negative pressure may appear along the pipeline, which will lead to pipeline damage. The power loss of the pump is calculated without any protective measures, and the specific results are shown in Figure 5.

It can be seen from Figure 5(a) that when the pump loses power, the pressure after the pump begins to drop, and when $t > 2.6$ s, the pressure after the pump drops to negative pressure. When $t = 16$ s, the pressure after the pump reaches the minimum value −2.14 m. It can be seen from Figure 5(b) that the maximum pipeline pressure meets the maximum pipeline pressure control standard (21.54 m < 28 m), but the minimum pressure in most places along the pipeline is negative. In order to ensure

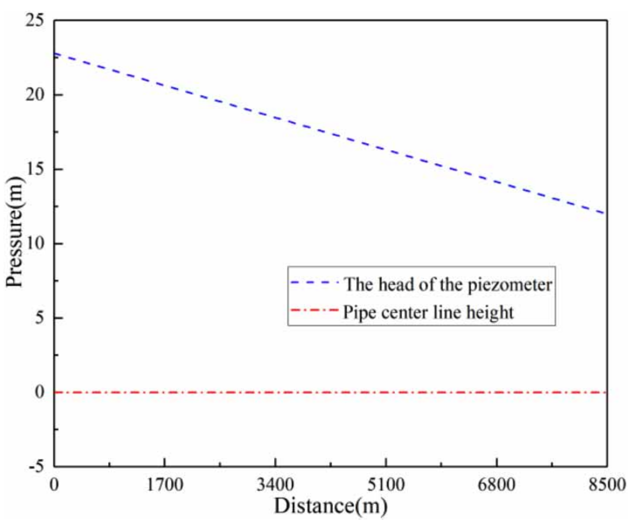

Figure 4 | Schematic diagram of piping layout for water supply system.

the safe and stable operation of the water supply system, it is necessary to set up reasonable protective measures to protect the negative pressure.

One-way surge tank protection

The project intends to adopt a one-way surge tank as a water hammer protection measure, and set it near the pumping station building, 10 m away from the junction of the pump outlet pipe. The relevant parameters of the one-way surge tank to be set in the water supply project can be obtained by numerical simulation calculation, with a cross-sectional area of 12.56 m^2 and a surge tank height of 15 m. In the case of power failure of the water pump, the resistance hole diameter ratio is taken as 0.2, 0.3, 0.4, 0.5, 0.6, and 1 for calculation.

It can be seen from Table 1 and Figures 6–8 that when the impedance size ratio increases gradually, the maximum pressure behind the pump is always 22.82 m, and the minimum pressure behind the pump increases from 0.54 m to 1.31 m, but the change range of the pressure after the pump decreases. The maximum pressure at the bottom of the one-way surge tank is always 22.79 m, and the minimum pressure at the bottom of the one-way surge tank first increases from 0.75 m to 6.67 m and then decreases gradually to 5.90 m. The water level of the one-way surge tank dropped continuously from 11.28 m to 5.90 m.

After that, the pressure began to increase by a large margin, and it showed a regular attenuated oscillation at the end of the water supplement ($t = 153$ s). When the impedance size is 0.5, 0.6, and 1.0, the bottom pressure of the one-way surge tank suddenly drops to a certain value in a short time and then continues to drop. This value is 9.25 m, 10.95 m, and 12.86 m, respectively. At the end of water supply, the pressure reaches its minimum value, which is 6.67 m, 6.28 m, and 5.90 m, respectively. The pressure then rises and carries out regular attenuation oscillation.

The water level of the one-way surge tank shows a trend of a fast initial drop and then a slower drop until the water level no longer drops, and the larger the impedance hole size, the faster the water level of the one-way surge tank drops. When the impedance size ratio changes from 0.2 to 0.5, the water level of the one-way surge tank differs greatly,

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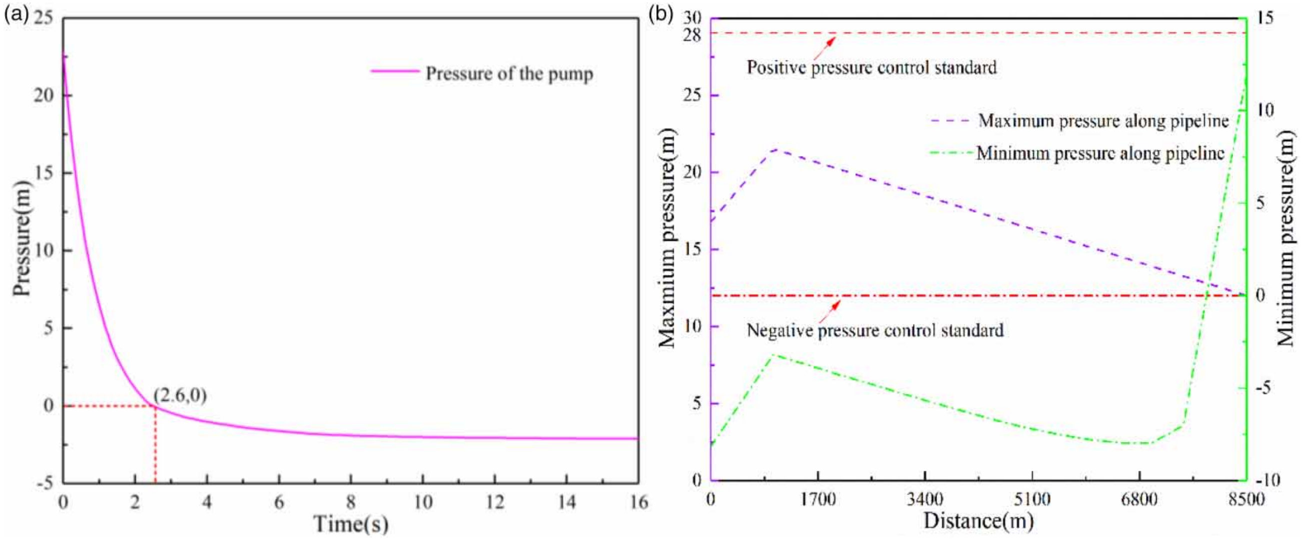

Figure 5 | (a) Pressure change after the pump is powered off; (b) pipeline pressure envelope without protection.

Table 1 | Calculation results of different impedance hole sizes

Impedance hole diameter ratio	Pressure after pump (m)			Bottom pressure of one-way surge tank (m)			Water level of one-way surge tank (m)		
	Max	Min	Amplitude	Max	Min	Amplitude	Max	Min	Amplitude
0.2	22.82	0.54	22.28	22.79	0.75	22.04	14	11.38	2.62
0.3	22.82	1.02	21.80	22.79	2.37	20.42	14	9.20	4.80
0.4	22.82	1.17	21.65	22.79	4.78	18.01	14	7.54	6.46
0.5	22.82	1.25	21.57	22.79	6.67	16.12	14	6.68	7.32
0.6	22.82	1.28	21.54	22.79	6.28	16.51	14	6.28	7.72
1.0	22.82	1.31	21.51	22.79	5.90	16.89	14	5.90	8.10

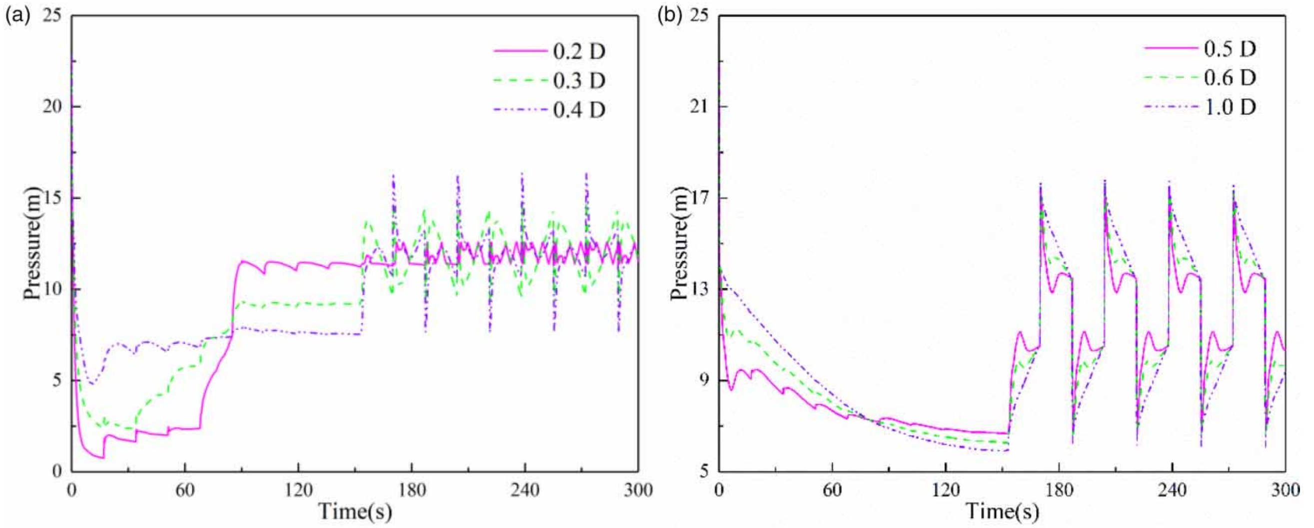

Figure 6 | Process line of pressure change at the bottom of one-way surge tank.

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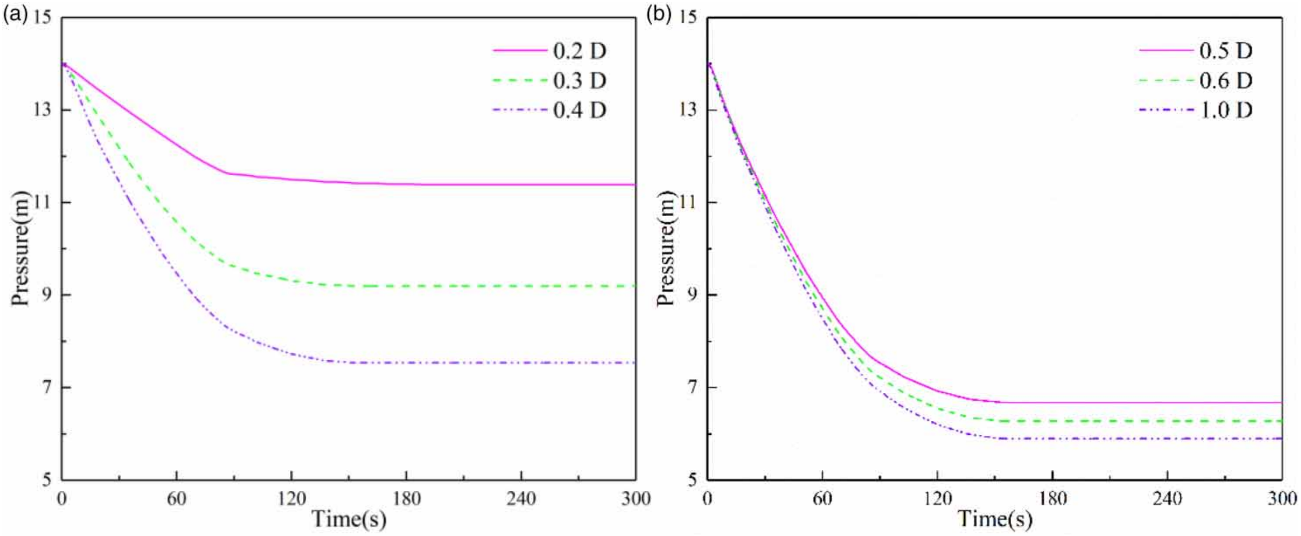

Figure 7 | Process line of water-level change of one-way surge tank.

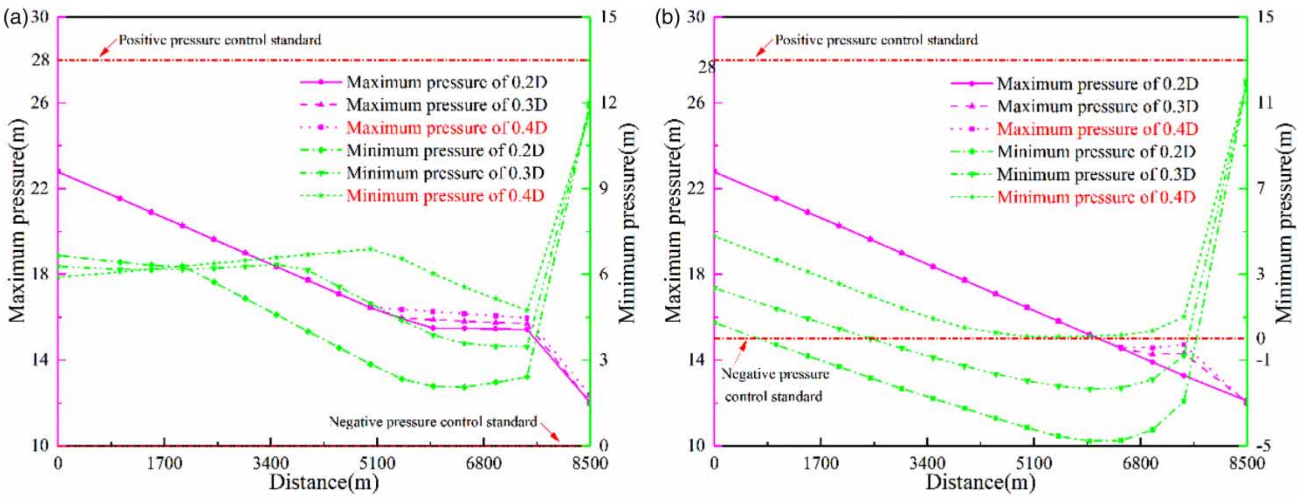

Figure 8 | Maximum and minimum pressure envelope of water supply system.

and the water level of the surge tank decreases by 4.7 m. When the impedance dimension ratio changes from 0.5 to 1.0, the water level of the surge tank only decreases by 0.78 m.

When the impedance hole size ratio is 0.2 or 0.3, the water head loss of the impedance hole is too large due to the small impedance hole, which makes it difficult to flow into the pipeline in the one-way surge tank, resulting in an insufficient water supply capacity for the pipeline. Under the influence of the first wave of water hammer pressure reduction, the water supply system has different degrees of negative pressure. When the impedance hole size ratio is 0.4–1.0, the pressure drop along the pipeline is controlled due to the small pressure drop caused by the impedance, which has a negative pressure protection effect. When the impedance hole size ratio increases from 0.2 to 0.5, there is a large change in the system pressure and water level in the surge tank change; however, when the impedance hole size ratio increases from 0.5 to 1.0, the change range is small, that is, when the impedance hole reaches a certain value, increasing its size has little effect on the bottom pressure and the water-level change range in one-way surge tanks.

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DISSCUSSION

For this project, a one-way surge tank is set at the pump outlet, where the initial pipeline pressure (refers to the water head of the pressure measuring pipe based on the pipe axis) is 22.79 m. The height of the top of the surge tank is 14.0 m, and the actual height of the surge tank is 14.0 m because the pipe axis is 0.0 m. The impedance loss at the one-way surge tank is H_ω. When the water pump is cut off, the one-way surge tank responds quickly, and the water hammer pressure of $22.79–14.0 - H_\omega = 8.79\ \text{m} - H_\omega$ continues to spread downstream through the bottom of the one-way surge tank.

The impedance loss is closely related to the impedance size of the one-way surge tank, and the smaller the impedance hole size, the greater the impedance loss of the surge tank. Therefore, it can be found from Figure 6 that in a short time, the pressure at the bottom of the one-way surge tank drops rapidly, but both the magnitude and value of the decrease gradually reduce. If the impedance hole size ratio is greater than 0.5, the penetration pressure drop caused by the impedance loss is already very small, and the difference is only 1.91 m from 0.6 to 1.0, which also conforms to the relationship between the impedance hole size and the penetration pressure drop. However, due to the limited area of the surge tank, with the increase of the size of the impedance hole, the flow rate of the one-way surge tank to make-up water into the pipeline increases. Under the action of inertia, the water body continues to drop, which will cause head loss. Therefore, when the impedance hole size is greater than 0.5, the pressure at the bottom of the one-way surge tank will continue to decrease after the first wave of penetration pressure drop until the water is replenished. At this time, the bottom pressure of the one-way surge tank is mainly determined by head loss. In the process of changing from 0.5 to 1.0, the bottom pressure of the one-way surge tank shows a decreasing trend, but the difference between different impedance ratios is not large.

Due to the friction h_ω in the pipeline, the pressure transmitted to downstream is $12.79 - H_\omega - h_\omega$. Since the water pressure line along the downstream direction of the pipeline is gradually reduced, negative pressure may occur in the downstream where the initial water pressure line is less than $12.79 - H_\omega - h_\omega$.

For a one-way surge tank with a small impedance hole size, H_ω is too large, the make-up water flow is small, and the influence of h_ω is small, so negative pressure is likely to occur. In addition, when the impedance size ratio changes from 0.2 to 0.4, the impedance loss changes in order of magnitude. Therefore, increasing the impedance size can effectively reduce the negative pressure, and, as shown in Figure 8, the pressure at each point of the pipeline changes regularly. The larger the impedance hole size, the greater the minimum pressure corresponding to each point; however, when the size of the impedance hole continues to increase to 0.5, there is no significant difference in impedance loss. The increase of the impedance hole will cause the flow in the pipeline to increase, leading to an increase of h_ω, but the impact of h_ω on the pipeline is small, so it is better protected against the negative pressure of the water supply system. In the process of impedance size ratio from 0.6 to 1.0, the pressure in the pipeline shows a trend of first rising, then falling, and then rising. The first wave of rise is due to the pressure rise caused by more water filling in the pipeline, and the larger the size of the impedance hole, the more water is added and the longer the pressure rise distance. Until all the water has replenished, the pressure shows a downward trend under the influence of friction in the pipeline. At a location close to the lower reservoir, the pressure will continue to rise to the water pressure in the lower reservoir because the lower reservoir has a protective effect on nearby pipelines.

CONCLUSION

According to the impact of the one-way surge tank impedance on the water supply system of the pumping station, the impedance size of the one-way surge tank is optimized. The selection principle of impedance hole size was analyzed. There was no negative pressure in the pipeline and no leakage in the one-way surge tank. The relationship between the size of the impedance hole and the penetration pressure drop behind the pump and the make-up water flow rate of the one-way surge tank were derived. The selection range of impedance hole size was determined, and the minimum size of impedance hole of the one-way surge tank should be greater than 0.2 times the pipe diameter. The

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maximum size should reduce the amount of make-up water as much as possible on the basis of ensuring that there is no negative pressure in the pipeline.

At the same time, combined with the optimization calculation of the impedance hole size of the one-way surge tank in the water supply system of a pump station, the influence of the impedance hole size on the pressure after the pump, the bottom pressure of the one-way surge tank, the make-up water flow, the pressure along the pipeline, and other factors were analyzed. It can be seen from the results that when the impedance hole reached a certain value, increasing its size had little effect on the pressure change range of the water supply system and the water-level change range of the one-way surge tank.

Therefore, on the premise of ensuring that there is no negative pressure along the pipeline, the smaller impedance hole size should be selected as much as possible to reduce the water-level drop in the one-way surge tank, in order to reduce the installation elevation at the bottom of the one-way surge tank and the amplitude of pipeline pressure fluctuation. This study provides theoretical support for how to reasonably select the size of the impedance hole of the one-way surge tank in the water hammer protection process. In practical engineering, the protection effect of water hammer is also affected by the location, height, area, and other factors of the one-way surge tank, and so the optimal choice of the impedance hole size of the one-way surge tank in practical engineering needs further study.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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