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Negative pressure protection with one-way surge tanks in bidirectional water delivery systems

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ABSTRACT

Water hammer protection is one of the key factors for the safe operation of the long-distance water delivery systems, which has lots of useful results. However, the protection experiences for bidirectional water delivery systems using the same pipeline are lacking. In this study, the protection method with one-way surge tanks in the bidirectional water delivery system is investigated. The theoretical formula for one-way surge tank setting is derived based on the theory of water hammer propagation, and the pump head and bidirectional water hammer protection constraints. Subsequently, the pump trip transient processes in an actual system are simulated. Finally, different kinds of one-way surge tank protection schemes are compared. The results show that the pressure along the pipeline after the pump trip can meet the standard when using the one-way surge tank protection scheme calculated by the theoretical formula. The proposed method can provide the effective protection strategy for the bidirectional water delivery systems.

Key words: bidirectional water delivery, long-distance water delivery system, one-way surge tank, water hammer protection

HIGHLIGHTS

- Negative pressure protection for the bidirectional water delivery systems in the same pipeline is studied.
- The theoretical formula for one-way surge tank setting in bidirectional water delivery system is presented.
- The proposed one-way surge tank setting strategy can provide effective water hammer protection for the system.

INTRODUCTION

Long-distance water delivery is one of the most efficient ways to enhance the utilization of water resources and address the uneven temporal-spatial distribution of these resources. Bidirectional water delivery is indispensable when two locations serve as backup water sources. Bidirectional water delivery with the same pipeline system can increase the utilization of water resources, decrease investment, and reduce engineering design difficulty. The operation of the bidirectional water delivery system is complicated, and it will become unstable if the protection measure is improperly chosen.

Pump trip is the main threat to water delivery systems. When the pump is unintentionally powered off, the pressure after the pump drops quickly, and the pressure drop wave propagates downstream. In the pipeline, some locations have high elevations and lower initial internal water pressure (Simpson & Bergant 1994; Kim *et al.* 2014). The liquid column separation phenomenon may happen when the pressure drops below the vapor pressure. The phenomenon significantly threatens the system's safety, which may result in a pipe break. The negative pressure protection design is necessary for the projects to avoid potential damage (Verhoeven *et al.* 1998; Moghaddas *et al.* 2017).

One-way surge tanks, surge tanks, air valves, and air vessels are usually safety protection measures in long-distance supply systems (Chaudhry 2014; Besharat *et al.* 2017; Peng & Guo 2019). The internal pressure in the pipeline at the high points is small. When the pump is powered off, the pressure at these local high points may decrease below the vapor pressure, causing liquid column separation. These local high spots are where one-way surge tanks are placed. To prevent the separation of liquid columns from the pipeline and guarantee the water pipeline's safety, one-way surge tanks can be installed at a suitable place, and water can be injected into the pipeline when the pressure drops.

Numerous studies about water hammer have been conducted to secure long-distance water delivery systems. El-Dabaa & Khorais (2018) use an actual project as an example to examine the effects of the dimensions, the connection equivalent resistance, and the initial state parameter on the air vessel to maximize performance and minimize hazardous problems. The results indicate that these parameters greatly influence the system's protection against transient problems when using the air vessel. Wan & Huang (2018) provide the MacCormack time marching scheme to analyze a variable-property series pipe system, build a mathematical model, and predict the transient pressure and flow velocity. It is evident that the results generated by the improved method closely match the experimental findings. Asiaban & Fathi-Moghadam (2018) investigate the probability of the porous structure increasing the head loss at surge tanks throttle and simulate load rejection in hydropower plants through experiments. The results demonstrate that porous throttling is superior to conventional orifice throttling. Wan & Zhang (2018) performed a numerical analysis of the connector using the method of characteristics (MOC) to enhance the surge tank's performance. They then propose an intelligent self-controlled surge tank that can select connectors with varying flow capacities and demonstrate its advantages in pressure control. Yazdi *et al.* (2019) studied the protective measures installed in the water delivery pipeline and its optimal size, providing a theoretical basis for subsequent research. Bostan *et al.* (2019) studied the optimum design of shock absorbers for complex water distribution systems containing air vessels. They found that the nonlinearity of the momentum equation of such systems makes it impossible to solve. Bettaieb & Taieb (2020) conducted a transient study using a MATLAB code based on the MOC with linear integration, and they thoroughly analyzed the water hammer control strategy of pumping stations. The results indicate that transient pressure interference in water distribution networks can be considerably reduced in some situations by combining basic water hammer control devices. To provide theoretical guidance for the rational selection of air valves in practical engineering, Li *et al.* (2022) explain the structure and working principles of two different types of air valves and develop the mathematical model using MATLAB.

Wylie *et al.* (1993) studied how hydraulic impedance affected hydraulic vibration and offered a method for figuring out a surge tank's hydraulic impedance. To protect against low-head pipeline negative pressure, Stephenson (2002) advised using a one-way surge tank. Liu *et al.* (2002) conducted field tests to demonstrate the one-way surge tank's ability to protect against the phenomenon of liquid column separation and re-bridge, which is the basis for actual systems. A genetic algorithm was employed by Liu *et al.* (2008) to maximize the size of the one-way surge tank after they had looked at the underlying reasoning and mathematical model. Their results align with technical examples and provide a theoretical basis for more research. Zhang *et al.* (2011) created the series one-way surge tank layout concept and optimized it with numerical simulation to provide a theoretical framework for prospective systems.

However, the bidirectional water delivery in the same pipeline has yet to receive much attention. Previous studies have thoroughly examined the selection of protective measures in unidirectional long-distance water delivery systems. It is challenging to select a protective measure for bidirectional water delivery in the same pipeline, and it cannot be done just using the traditional water delivery protective measure selection criteria. This study deduces the setting principle of one-way surge tanks in the case of bidirectional water delivery based on the MOC. It verifies it by using numerical simulation in an engineering example. This study solves the complex protection problem of bidirectional long-distance water delivery projects and provides a reference for such systems.

MATHEMATICAL MODEL

The one-way surge tank's control equation is given as follows:

Flow continuity equation:

$$Q_{P2} = Q_{st} + Q_{P1} \tag{1}$$

where Q_{st} denotes the flow rate from the throttle orifice of the one-way surge tank (positive when flowing out); Q_{P1} denotes the transient flow before the one-way surge tank, and Q_{P2} denotes the transient flow behind the one-way surge tank. Equation (1) demonstrates the continuity and balance of transient flow within the pipeline.

Water head balance equation:

$$H_P = Z_{st} - kQ_{st}|Q_{st}| \tag{2}$$

where H_P denotes the pipeline's transient water head at the one-way surge tank's bottom; Z_{st} denotes the water level of the one-way surge tank; and k denotes the impedance head loss coefficient.

Relationship between flow rate and water level:

$$dZ_{st}/dt = -Q_{st}/A_{st} \tag{3}$$

The relationship between the one-way surge tank's intake and outflow flow and water level is expressed by Equation (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 C_{P1}, B_{P1}, C_{M2}, and B_{M2} denote the known quantities at the previous time on the MOC grid, and their values are related to factors such as pipeline parameters.

Analysis of negative pressure protection

Long-distance water delivery systems typically involve pumping stations with a pressurized flow. A significant negative pressure will endanger the water delivery system if no protective measures are in place during the pump trip. Surge tanks are a typical protective measure in long-distance water delivery systems but have rigorous topographic and geological constraints.

The bidirectional water delivery system's pipeline configuration is primarily uphill and downhill. In these systems, one-way surge tanks are typically constructed to protect the pipeline during pump trip. In addition, the one-way surge tank at the pipeline's fixed position should protect the system in both directions. In light of this, the one-way surge tank protection strategy is complex and vital. The front-end pipeline near the pump station experiences negative pressure when the pump trip happens. So, an air vessel is always installed at the outlet of the pumping station to protect the system.

In the pipeline, the one-way surge tanks are usually sat at humps to prevent the negative pressure. When the pressure is lower than the water level in the one-way surge tank, the one-way valve at the bottom of the tank will open to refill water in the pipeline. It stops the liquid column from separating. The architecture of a one-way surge tank is straightforward and less affected by geography. On the other hand, the one-way surge tank has a protective impact on the pipelines around it, which can considerably increase the safety of the water delivery pipeline.

However, one-way surge tanks do have certain restrictions, such as heights and cross-sectional area. If the cross-sectional area is too small, a one-way surge tank's water level might easily decrease too quickly or leak. Conversely, if it is large, the system investment will improve, and the construction will be more complicated. The impact of the height is the same as well. In addition, the one-way surge tank's illogical placement will impact the protective effect. As a result, the theoretical methods for selecting the one-way surge tank layout position, height, cross-sectional area, and throttle orifice size are crucial.

Theoretical derivation of the one-way surge tank setting strategy

Considering the pressure reduction after the pump stop is noninstantaneous, the protection plan of the water delivery system in Figure 1 is examined without taking into account the water hammer wave attenuation. The pipeline section before the one-way surge tank is protected. This protection is achieved by reflecting the water hammer wave from the one-way surge tank. An air vessel can be installed after the pumping station if the pressure drop is too significant. However, due to a lack of protective measures, the piezometric head decreases rapidly. The initial internal water pressure is low at local high points. When the

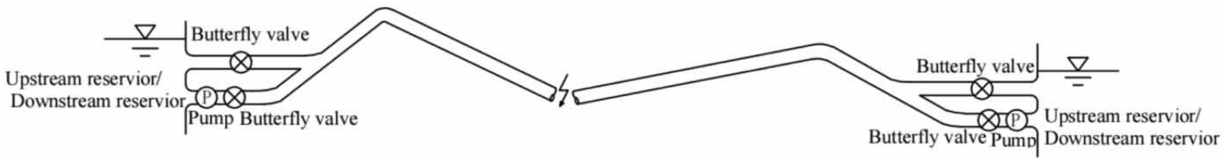

Figure 1 | Bidirectional water delivery system layout.

pressure drop wave spreads to high points in the pipeline, it is easy to produce negative pressure at these locations. So, the one-way surge tanks are generally seated at the local peaks of the pipeline to prevent negative pressure.

Figure 2 illustrates the scenario of a pump trip in the positive direction of water delivery. The length of the upstream reservoir's protection at the line's beginning is L_{1st}. When the pump is powered off, the pressure after the pump decreases linearly by ΔH_A. T_S is the time it takes. If there are n local high points with one-way surge tanks, the angles between the low point of the line and the horizontal plane are $\alpha_1, \alpha_2 \ldots \alpha_{2n}$, and the lengths of the corresponding pipeline are $L_1, L_2 \ldots L_{2n}$. The angle formed by the piezometric head line and the horizontal line is β. It is expected that the one-way surge tanks installed at each local high point have heights of $h_1, h_2 \ldots h_n$. In the reverse direction of water delivery, the upstream reservoir's protection length at the line's beginning is L_{1st}'. When the pump is powered off, the pressure after the pump decreases linearly by $\Delta H_A'$. T_S' is the time it takes.

The rated head of the pump limits the height of the one-way surge tanks. That is:

$$H \leq H_R \tag{5}$$

$$H' \leq H_R' \tag{6}$$

where H denotes the total head of the system in the case of positive water delivery; H_R denotes the rated head of the pump in the case of positive water delivery; H' denotes the total head of the system in the case of reverse water delivery; and H_R' denotes the rated head of the pump in the case of reverse water delivery.

When α and β are constants, the protection length of a one-way surge tank to its front section is expressed as follows (Zhang *et al.* 2011):

$$x_u = h \frac{T_S / \Delta H_A}{\dfrac{2}{a} - \dfrac{T_S \sin(\alpha + \beta)}{\Delta H_A \cos\alpha}} \tag{7}$$

where ΔH_A denotes the linear decrease value of the pump pressure without protective measures.

Similarly, the protection length of the one-way surge tank to the back is expressed as follows (Zhang *et al.* 2011):

$$x_d = h \frac{\cos\alpha}{\sin(\alpha + \beta)} \tag{8}$$

Regarding the positive direction of water delivery, the first local high point is adjacent to the pumping station. Pipeline L_1 can be protected by the first one-way surge tank and upstream reservoir. To prevent negative pressure in the pipeline, h_1 should satisfy:

$$L_{1st} + h_1 \frac{T_S / \Delta H_A}{\dfrac{2}{a} - \dfrac{T_S \sin(\alpha_1 + \beta)}{\Delta H_A \cos\alpha_1}} \geq L_1 \tag{9}$$

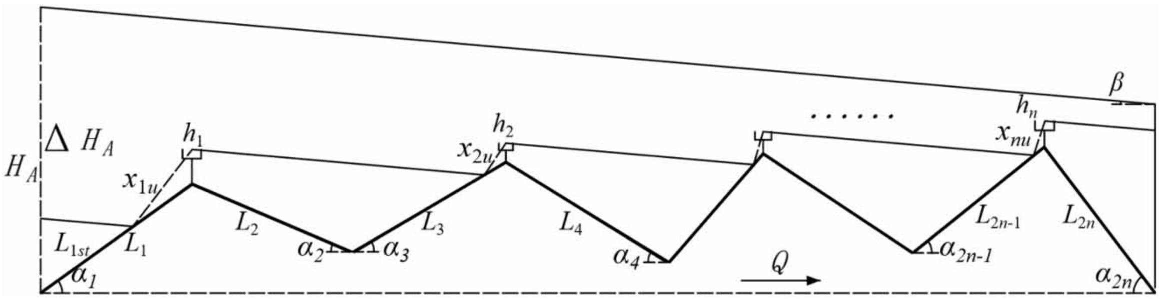

Figure 2 | Protection schematic diagram under positive direction of water delivery.

As shown in Figure 2, L_2 and L_3 are jointly protected by the first and second one-way surge tanks. Hence, h_1 and h_2 should satisfy:

$$\frac{h_1 + L_2(\sin\alpha_2 + \cos\alpha_2 \tan\beta)}{\sin\alpha_3 + \cos\alpha_3 \tan\beta} + h_2 \frac{T_S/\Delta H_A}{\frac{2}{a} - \frac{T_S \sin(\alpha_3 + \beta)}{\Delta H_A \cos\alpha_3}} \geq L_3 \tag{10}$$

Similar requirements should also be met for setting the one-way surge tanks behind L_3.

The sum of the protection length of the nth one-way surge tank and the *(n–1)*th one-way surge tank to the $L_{2n\text{-}1}$ section of the pipeline must be greater than or equal to the length of $L_{2n\text{-}1}$.

$$\frac{h_{n-1} + L_{2(n-1)}(\sin\alpha_{2(n-1)} + \cos\alpha_{2(n-1)} \tan\beta)}{\sin\alpha_{2n-1} + \cos\alpha_{2n-1} \tan\beta} + h_n \frac{T_S/\Delta H_A}{\frac{2}{a} - \frac{T_S \sin(\alpha_{2n-1} + \beta)}{\Delta H_A \cos\alpha_{2n-1}}} \geq L_{2n-1} \tag{11}$$

Similarly, as shown in Figure 3, in the case of the reverse direction of water delivery, the height of one-way surge tanks should satisfy:

$$L_{1st}' + h_n \frac{T_S'/\Delta H_A'}{\frac{2}{a} - \frac{T_S' \sin(\alpha_{2n} + \beta')}{\Delta H_A' \cos\alpha_{2n}}} \geq L_{2n} \tag{12}$$

$$\frac{h_2 + L_3(\sin\alpha_3 + \cos\alpha_3 \tan\beta')}{\sin\alpha_2 + \cos\alpha_2 \tan\beta'} + h_1 \frac{T_S'/\Delta H_A'}{\frac{2}{a} - \frac{T_S' \mathit{sin}(\alpha_2 + \beta')}{\Delta H_A' \cos\alpha_2}} \geq L_2 \tag{13}$$

It should be noted that when there is only one local high point in the pipeline and only a one-way surge needs to be sat, the water delivery system behind it is gravity flow. Thus, there is no need to consider the protection length behind the one-way surge tank.

Hence, in the positive direction of water delivery, h_1 should satisfy:

$$L_{1st} + h_1 \frac{T_s/\Delta H_A}{\frac{2}{a} - \frac{T_S \sin(\alpha_1 + \beta)}{\Delta H_A \cos\alpha_1}} \geq L_1 \tag{14}$$

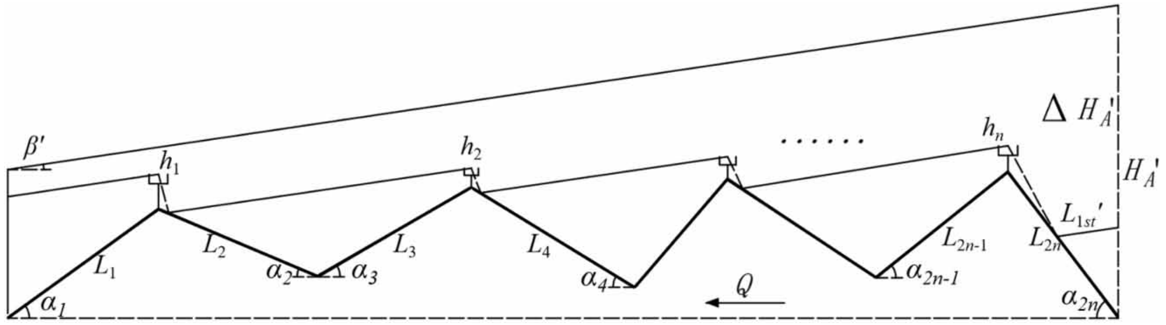

Figure 3 | Protection schematic diagram under reverse direction of water delivery.

In the reverse direction of water delivery, h_1 should satisfy:

$$L_{1st}' + h_1 \frac{T_s'/\Delta H_A'}{\dfrac{2}{a} - \dfrac{T_s' \sin(\alpha_2 + \beta')}{H_A' \cos \alpha_2}} \geq L_2 \tag{15}$$

CASE STUDY

A practical project is used to verify the formula in this study. Figure 4 shows a bidirectional water delivery system with two conspicuous high points. The detailed parameters are shown in Table 1. The water delivery pipeline spans a length of 32.29 km. Point B and Point D are two obvious high points in the pipeline. Regarding positive water direction delivery, Point B is 16.57 km from the pump outlet, and point D is 23.65 km away from the pump outlet. The height of the points' centerline is 378.33 and 384.57 m, respectively. The diameters of the pipeline are 1.4 and 1.2 m. The angle between the piezometric head line and the horizontal plane is $\beta = 0.04°$ in the case of the positive direction of water delivery and $\beta' = 0.06°$ in the case of the reverse direction of water delivery. The pressure standard of the system is that the maximum pressure of the water delivery pipeline must be less than 198 m, and there must be no negative pressure.

As illustrated in Figure 4, the vertical height difference of the pipeline is small and negligible relative to the horizontal length. L_1 and L_4 can be regarded as the horizontal length of AB and DE sections of pipe. In calculating the angle between the pipeline and the horizontal plane α_1 *and* α_4, the tangent value of the angle is derived using the vertical height difference ratio between the two points to the horizontal distance. Selecting a reasonable point C to calculate L_2, L_3, α_2, *and* α_3 is vital. The elevation of the pipeline between points B and D in Figure 4 tends to reduce first and then grow, and the lowest point

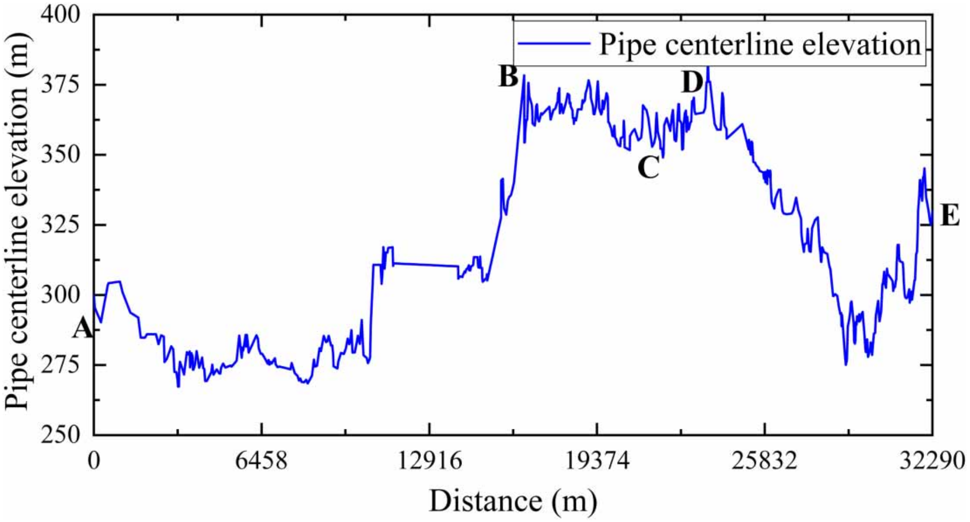

Figure 4 | Pipe centerline elevation.

Table 1 | Parameters of water delivery system

Positive direction of water delivery		**Reverse direction of water delivery**	
Upstream reservoir's water level (m)	304	Upstream reservoir's water level (m)	335
Downstream reservoir's water level (m)	335	Downstream reservoir's water level (m)	304
Main pipe flow (m^3/s)	1.2	Main pipe flow (m^3/s)	1.35
Rated head of pump (m)	110	Rated head of pump (m)	78
Actual head of pump (m)	108.6	Actual head of pump (m)	77.3

between points B and D is point C. It is 21.93 km away from the pump outlet with the 349.07 m elevation, and L_2, L_3, α_2, *and* α_3 can be calculated. The parameters are shown in Table 2.

The numerical simulation is conducted based on the MOC, and a mathematical model of the water delivery system is developed. Various operating conditions are chosen to satisfy the water delivery system's safety standards.

Pump trip without protection

The pressure in the pipeline downstream of the pump decreases abruptly after a pump trip happens. In Figures 5 and 6, the change in pump pressure and the envelope of the pipeline pressure following the pump station are given.

Figures 5(a) and 6(a) show that the maximum pressure of the water delivery system is 143.40 m without protective measures, which is less than the system pressure standard of 198 m. The water delivery system will produce immense negative pressure, which does not meet the pressure standard of the pipeline. It should be noted that the water in the pipeline will evaporate when the negative pressure is higher than −10 m. In that case, liquid column separation will occur and make the water delivery system unsteady. As a result, the pressure in Figures 5(a) and 6(a) below −10 m is a theoretical value that illustrates the severity of negative pressure.

In Figures 5(b) and 6(b), it can be seen that the pressure drop of the pump is about 54.47 m at 0.45 s after the pump is powered off by accident during the positive water delivery; in the reverse water delivery, the pressure drop of the pump is about 71.84 m after 0.45 s by accident. Therefore, $T_S = 0.45$ s, $\Delta H_A = 54.47$ m, $T_S{}' = 0.45$ s, and $\Delta H_A{}' = 71.84$ m.

Protective effects of one-way surge tanks

From the results of Figures 5 and 6, it can be seen that whether it is a positive or reverse water delivery, the pipeline will produce severe negative pressure after the pump trip happens without setting protective measures. As a result, to protect the negative pressure following the pump trip, it is necessary to install an air vessel at the outlet of the pumping station

Table 2 | Piecewise parameters of the pipeline

Length of pipe section (m)		The angle between the pipeline and the horizontal plane (°)	
L_1	16,574	α_1	0.27
L_2	5,339	α_2	0.31
L_3	1,740	α_3	0.22
L_4	8,637	α_4	0.35

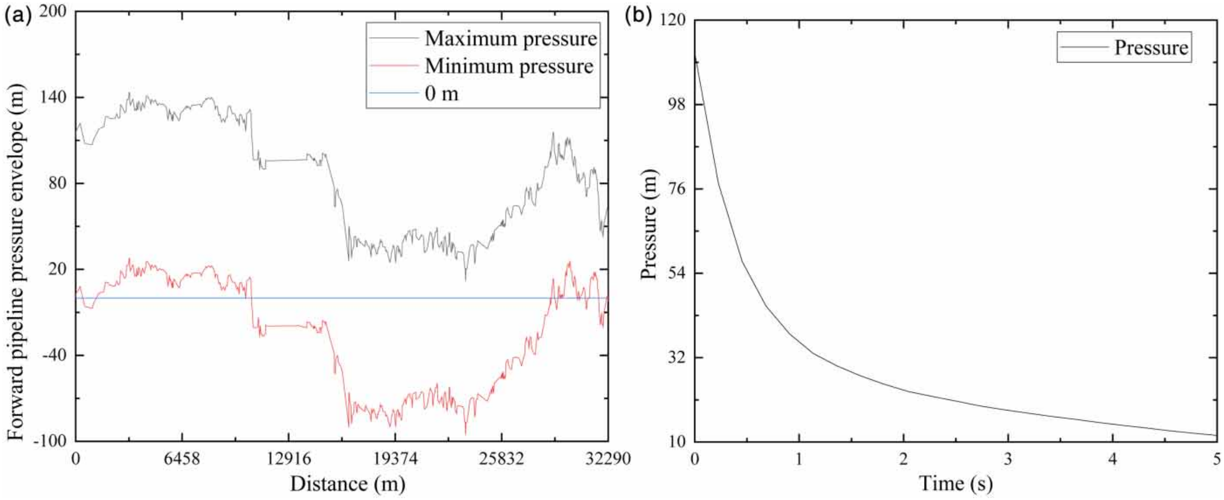

Figure 5 | (a) The envelope of positive water delivery pressure and (b) pressure change after pump station.

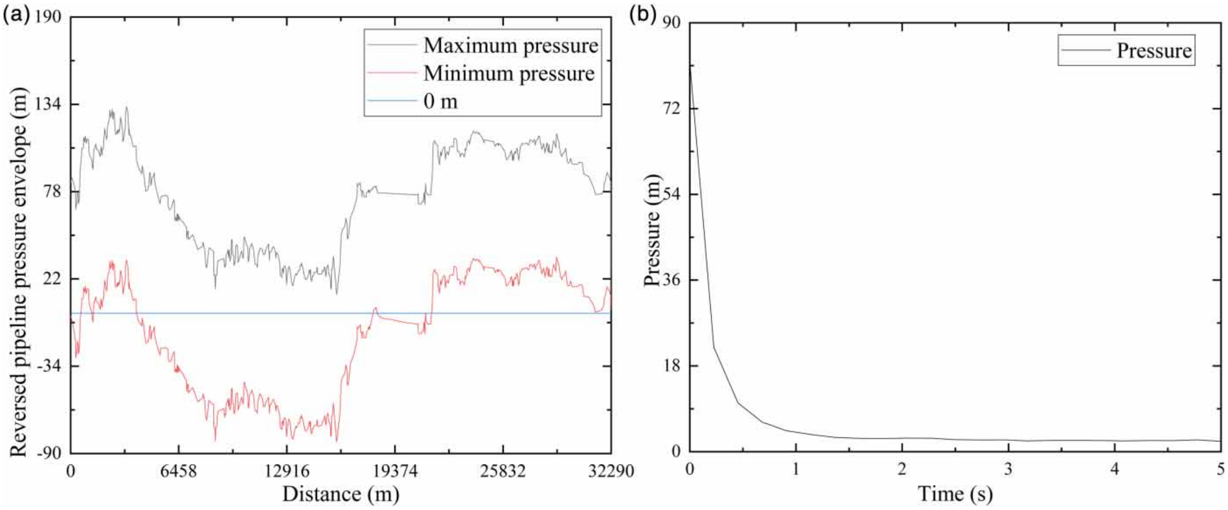

Figure 6 | (a) The envelope of reverse water delivery pressure and (b) pressure change after pump station.

and one-way surge tanks at the pipeline's apparent high points. The impedance coefficient of the throttle orifice of the one-way surge tanks is 0.8. The volume of the air vessel sat at point A is 10 m^3, and the volume of the air vessel sat at point E is 23 m^3. The throttle orifice diameter of the air vessels is 0.6 m. The pipeline's protective effects are better than single protection when the air vessel and one-way surge tank interact simultaneously. Therefore, for L_{1st}, L_{1st}', there is $L_{1st} \approx L_1$, $L_{1st}' \approx L_4$.

Hence, the one-way surge tank constructed at point B is called the 1# one-way surge tank, while the one constructed at point D is called the 2# one-way surge tank. The results are brought into Equations (5)–(13) to simplify the solution. Figure 7 displays the height range of each one-way surge tank.

As shown in Figure 7, h_1 ranges from 6.15 to 10.75 m, and h_2 ranges from 6.59 to 11.42 m. The rated head of the pump limits the upper limit boundary in the figure, and the negative pressure protection requirements restrict the lower limit boundary. Four groups of one-way surge tank protection schemes are selected from Figure 7 to verify the derivation in this study. It should be noted that, except for the height of the one-way surge tanks, the other parameters are kept constant. The cross-sectional area of each one-way surge tank is 38.5 m^2, and the throttle orifice diameter is 0.7 m. In Scheme 1, the height of 1# and 2# one-way surge tanks is only higher than the calculated minimum height. The height of the 1# one-way surge tank is 7 m, and the height of the 2# one-way surge tank is 7 m. In Scheme 2, the height of the 1# one-way surge tank is less than the

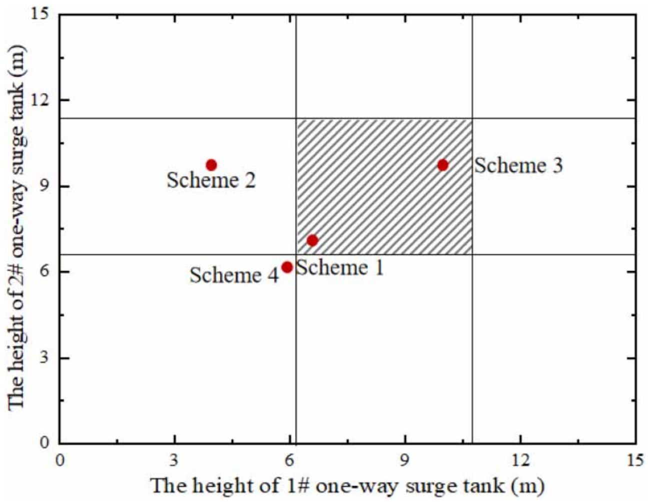

Figure 7 | Height range diagram of the one-way surge tanks.

calculated minimum height, but the sum of the two one-way surge tanks' height is consistent with Scheme 1. The height of the 1# one-way surge tank is 4 m, and the height of the 2# one-way surge tank is 10 m. In Scheme 3, the height of 1# and 2# one-way surge tanks is less than but close to the calculated maximum height. The height of the 1# one-way surge tank is 10 m, and the height of the 2# one-way surge tank is 10 m. In Scheme 4, the height of 1# and 2# one-way surge tanks is lower than the calculated minimum height. (Scheme 4 only meets the pressure standard for reverse water delivery.) The height of the 1# one-way surge tank is 6 m, and the height of the 2# one-way surge tank is 6 m. The one-way surge tank cannot operate properly if the height of the one-way surge tank is higher than the calculated maximum height. In that case, the one-way valve at the bottom of the one-way surge tank opens, and the one-way surge tank replenishes water to the pipeline, resulting in the unsteady pipe flow under a constant flow state, which does not meet the requirements.

In Scheme 1, the heights of one-way surge tanks meet the requirements of the solution results, and the cost is the most economical. In Scheme 2, the height of 1# one-way surge tank does not meet the formula requirements, but the total height of one-way surge tanks is consistent with Scheme 1. The heights of the one-way surge tanks in Scheme 3 meet the requirements of the solution results, but the cost is high. Scheme 4 is a protection plan that focuses solely on protecting the reverse water delivery. It is computed to find out if Scheme 4 can meet the protection criteria for forward water delivery. The results are shown in Table 3 and Figures 8–12.

As shown in Figure 8, the minimum pressure of Scheme 2 cannot meet the pipeline's pressure standard. Figures 9 and 10 show that the water in the one-way surge tanks of each scheme is not empty. Figure 11 shows the pressure change of each scheme's minimum pressure extreme point. Scheme 2 shows a poor protection effect. It can be seen in Figure 12, Scheme 4 does not meet the system safety requirements.

Table 3 | Numerical simulation results

	Positive water delivery			**Reverse water delivery**		
Scheme	**Maximum pressure (m)**	**Minimum pressure (m)**	**Minimum water level of one-way surge tank (m)**	**Maximum pressure (m)**	**Minimum pressure (m)**	**Minimum water level of one-way surge tank (m)**
Scheme 1	181.45	0.07	4.64/1.39	184.76	1.1	5.51/1.21
Scheme 2	176.04	−8.9	2.44/3.35	192.68	−0.05	3.88/2.78
Scheme 3	187.09	0.98	7.52/4.29	193.59	2.74	8.42/4.07
Scheme 4	179.56	−6.24	3.68/0.33	181.46	0.04	4.54/0.27

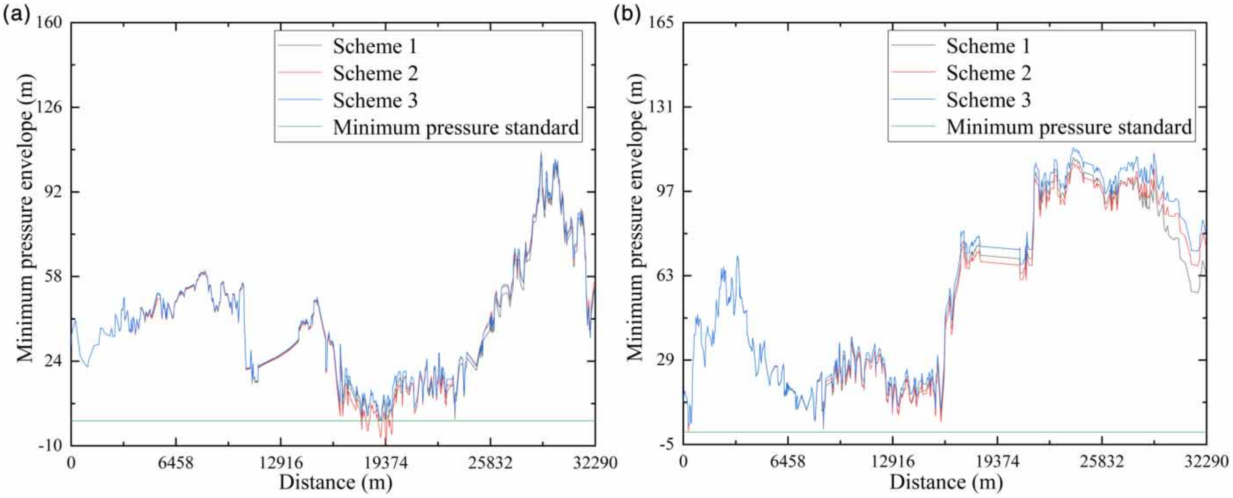

Figure 8 | Pipeline minimum pressure envelope: (a) positive water delivery and (b) reverse water delivery.

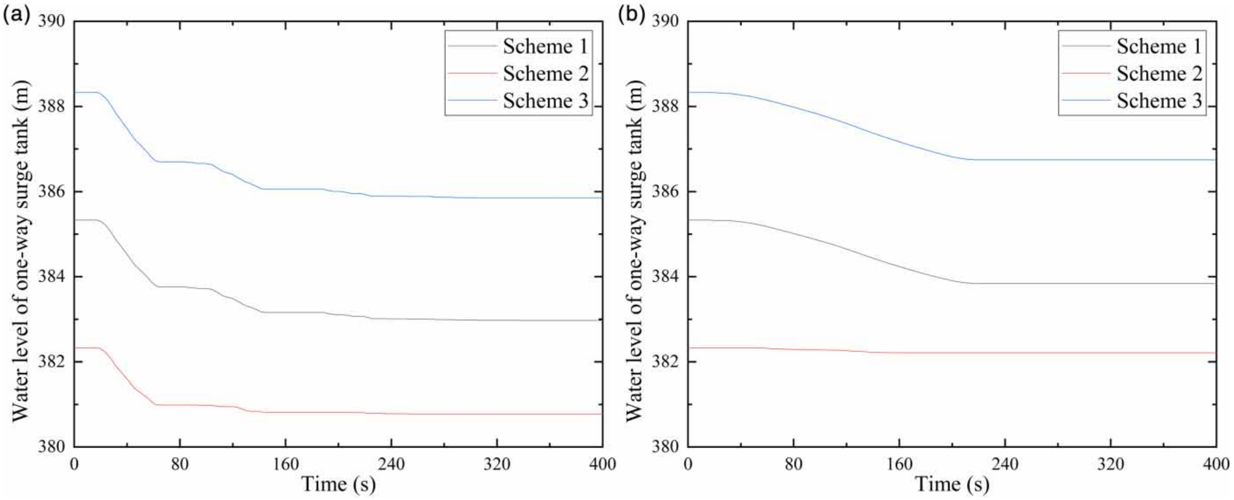

Figure 9 | Water level change of 1# one-way surge tank: (a) positive water delivery and (b) reverse water delivery.

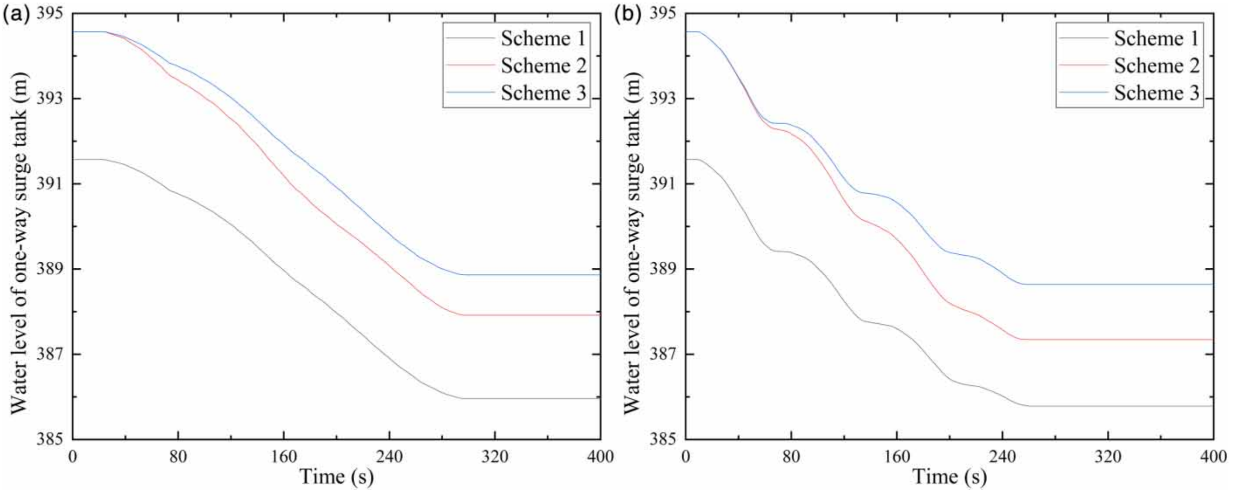

Figure 10 | Water level change of 2# one-way surge tank: (a) positive water delivery and (b) reverse water delivery.

This project does not emphasize the protection of the maximum pressure; thus, only the minimum pressure envelope is drawn. Each scheme's maximum pressure satisfies the pipeline's pressure-bearing requirement. Scheme 3 has the highest total height of the one-way surge tanks, and its maximum pressure is also the largest. In forward water delivery, the maximum pressure in Scheme 3 is 187.09 m, and it is 193.59 m in reverse water delivery. It should be noted that the maximum pressure of Scheme 3 for reverse water delivery is closer to the pressure standard of the maximum pressure of the pipeline.

The results show that each scheme's one-way surge tanks are not empty, which satisfies the protection requirement. Then, comparing the calculation results reveals that the maximum pressure of each scheme can meet the system pressure criteria. Since the minimum pressure is 8.9 m above the accepted level, Scheme 2 is not feasible. Both Scheme 1 and Scheme 3′s maximum and lowest pressures can meet the standard. However, the height of the one-way surge tanks in Scheme 3 is 6 m greater than that in Scheme 1. In other words, the height of the one-way surge tanks in Scheme 3 is 30% less than that in Scheme 1. Scheme 3′s minimum pressure is 0.91 m higher than Scheme 1.

Scheme 4 is not included in the formula solution set. Although Scheme 4 can guarantee system safety in the case of reverse water delivery, it will result in negative pressure in the case of forward water delivery. It is also not advised to implement this strategy because the 2# one-way surge tank's safe water depth is low.

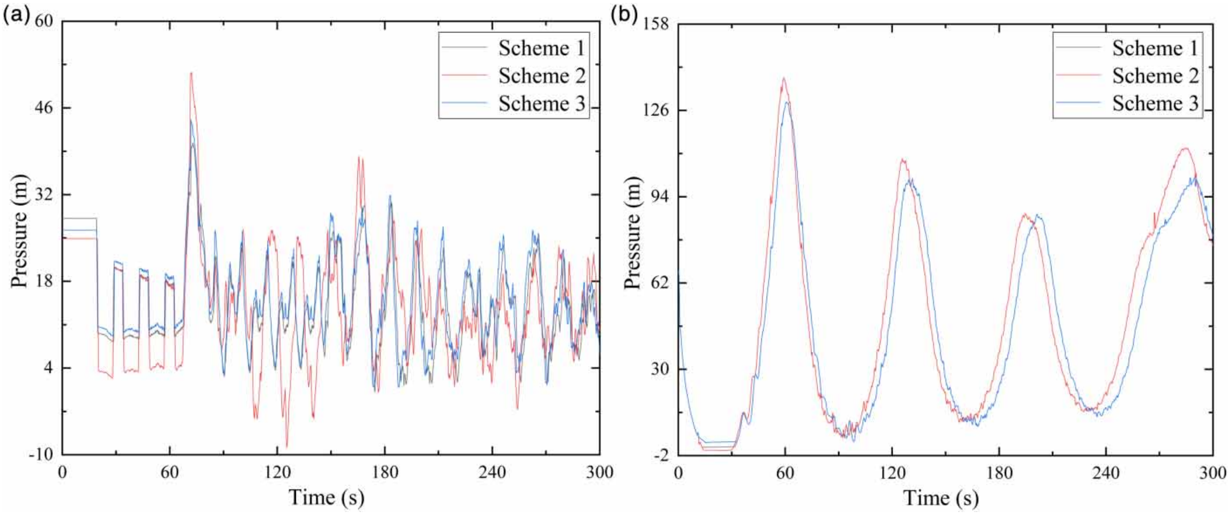

Figure 11 | Pressure change of the minimum pressure extreme point: (a) positive water delivery and (b) reverse water delivery.

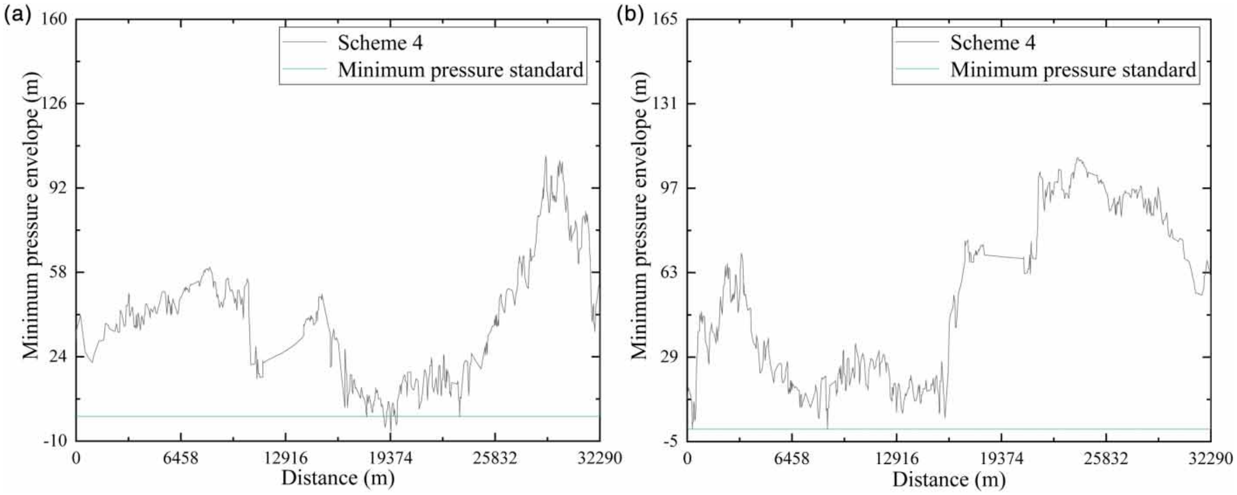

Figure 12 | Minimum pressure envelope for Scheme 4: (a) positive water delivery and (b) reverse water delivery.

The size of the one-way surge tanks must satisfy Equations (5)–(13) if the system is to operate securely in both directions. It is evident that the height of one-way surge tanks calculated by the theoretical formula is reasonable, and the method can accurately determine the height of one-way surge tanks.

DISCUSSION

This study deduces the formula for one-way surge tank height according to the existing studies and geometric relationship to analyze the bidirectional water delivery protective measures in the same water delivery pipeline. The mathematical model is then created using the MOC, and a numerical simulation is run to ensure the formula is accurate. This part will discuss the effect of the height of the one-way surge tanks on the pressure of the pipeline.

First, a plan that assumes the height of the one-way surge tanks does not satisfy the estimated conditions is constructed, known as Scheme 2. Furthermore, the one-way surge tanks' cross-sectional area and total height in this scheme are constant with Scheme 1. Results are displayed in Table 3. With the same overall height of the one-way surge tanks, Scheme 1′s lowest pressure was 8.97 m higher than the minimum pressure of Scheme 2, which is −8.9 m. The results show that when a one-way surge tank's size does not meet the requirements, the system's pressure standard will not be met even if the overall height of one-way surge tanks remains constant. Examine whether a protection scheme that only considers unidirectional water supply can meet the needs of the bidirectional water delivery system. Scheme 4 satisfies the reverse water delivery protection criteria; however, the height of the two one-way surge tanks in this scheme does not comply with the formula. It is calculated whether the scheme will ensure the safety of the system in forward water delivery to confirm the correctness of the formula derived in this work. Scheme 4's forward water delivery has a minimum pressure of -6.24 m, which is lower than the system's pressure standard. As a result, the protection criterion of a bidirectional water delivery system cannot be met by just taking one-way water delivery protection into account.

When the overall height of the one-way surge tanks is consistent in the system with a stable pipeline, the protective effect is not noticeably different. This study examines a bidirectional water delivery system with several ups and downs, which should consider protection from both directions. The traditional water delivery system's guiding concept cannot be used to choose the height of the one-way surge tanks. The pipeline's higher elevation section has a lower initial internal water pressure. Such locations are more likely to experience negative pressure during pump trip because of the propagation of the pressure drop wave. If the height of the previous one-way surge tank is low, there may be a substantial negative pressure in the pipeline before the pressure drop wave is transmitted to the one-way surge tank, making it operate. However, positioning two 7-m-high one-way surge tanks at two sites makes it possible to meet the system's pressure requirements and optimize the pump performance. As a result, the one-way surge tank heights installed must comply with the formula's specifications.

Secondly, previous studies on protecting long-distance water delivery systems are based on unidirectional long-distance water delivery systems. The theoretical formula is investigated in this study as it determines the protection plan for the bidirectional water delivery in the same water delivery pipeline. This study calculates the scheme that meets the formula requirements but has a higher total height of the one-way surge tanks, which is Scheme 3. As shown in Table 3, the results indicate that both Schemes 1 and 3 can meet the protection criteria. The maximum pressure of Scheme 1 is 8.76 m lower than that of Scheme 3, and the minimum pressure of Scheme 1 is 0.91 m lower than that of Scheme 3. Notably, the total height of the one-way surge tanks in Scheme 3 is 16 m, which is 1.6 times that of Scheme 1, leading to an associated increase in project costs. The protective effects of both schemes are comparable, with both successfully meeting the specified requirements. The comparison of Schemes 1 and 3 demonstrates the accuracy of the theoretical formula, which can serve as a theoretical basis for choosing such technical protection schemes and has some significance for engineering practice.

CONCLUSION

This study establishes a method for choosing a one-way surge tank protection strategy for bidirectional water delivery systems in the same water delivery pipeline. The formula is used to determine the height of the one-way surge tanks that satisfies engineering specifications, and an engineering example is used to confirm the formula's accuracy. This study offers a theoretical basis for further engineering. According to the results, the following main conclusions are drawn:

1. When choosing the one-way surge tank protection plan for the bidirectional water delivery system, consider placing the one-way surge tank at the line's obvious local high points. This placement can protect the system's safety and effectively counteract significant negative pressure.
2. In pressurized water delivery projects like this study, the total height and position of the one-way surge tanks are kept unchanged. However, if the size of any one-way surge tank does not meet the formula's requirements, the protection effect cannot meet the criteria. That proves this study's rationality for the one-way surge tank height formula.
3. If a higher one-way surge tank height is selected within the formula range, the difference between the results of this scheme and other schemes is small. As a result, when the size of the one-way surge tank is selected, the smaller height of the one-way surge tank can be chosen within the formula's range.

The influence of the pump's features and the attenuation of the water hammer wave were not considered while determining the theoretical formula. To further increase the formula's accuracy, it will be possible to research the impact of these aspects in the future.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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