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Study on water hammer protection of the siphon breaking structure in the water supply system

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ABSTRACT

An appropriate water hammer protective scheme is a significant concern in the operation of water supply projects. According to the special terrain in the water supply project, which forms a siphon breaking structure at the end of the pipeline, three protective schemes were proposed and compared: single vacuum breaking valve (VBV) scheme, VBV and air valve scheme, and VBV and one-way surge tower scheme. Based on the control standards of pipe pressure, the three protective schemes were assessed in terms of suppressing the negative pressure caused by a pump trip accident. The results show that the siphon breaking structure with the VBV can achieve good effect protection only in a limited range of pipelines. In the VBV and air valve scheme, the pressure oscillations were obviously caused by repeated inlet and exhaust of the air valves. To avoid supplementing too much gas in the pipe by air valves, which will result in a gas column bridging phenomenon, the VBV and one-way surge tower scheme is proposed and can better meet the requirement of the pressure control standard.

Key words: combined protective scheme, siphon breaking structure, vacuum breaking valve, water supply system

HIGHLIGHTS

- The water hammer protection according to the siphon breaking structure at the end of the pipeline has been proposed and improved.
- The two combined water hammer protections with VBV and one-way surge tower and air valves have been compared.
- The method of suppressing negative pressure have been discussed based on the conditions of the pipeline.

NOTATIONS

A_{in} A_{out}	Inlet and outlet flow area of the valve
$B_{P1}, B_{M2}, C_{P1}, C_{M2}$	State quantities related to the previous time t_0 in the characteristic compatibility equation of water hammer
C^+, C^-	Characteristic compatibility equation of water hammer
C_{in}, C_{out}	Inlet and outlet flow coefficients of the valve
H_a	Atmospheric head (absolute head)
H_p	Pressure head of the pipeline node
H_{pi}	Pressure head of the pipeline of section i
i	Pipe section
m	Air mass
m_0	Air mass at time t_0
M	Molar mass of gas
P	Pressure inside the pipe
P_0	Local atmospheric pressure
Q_{pxi}, Q_i	Inflow and outflow of section i at time t_0
Q_{ppi} Q_{pi}	Inflow and outflow of section i at time t
R	Molar gas constant
t	Time
Δt	Time increment
T T_0	Inside and outside temperatures of the pipe

V_0 V	Initial volume of the hole and the volume of the air in the pipeline, respectively
Z	Elevation of the vacuum breaking valve position
ρ_0	Atmospheric density
γ	Liquid bulk density

INTRODUCTION

The rapid development of rural urbanization and large-scale agriculture has led to the increase of regional water demand. Due to the uneven distribution of water resources, the water supply project has become an effective way to solve this problem. With the increasing number of water supply projects, people pay more and more attention to the safety of project operations. Implications of transient research for urban water supply system management have been discussed. Efficiency and safety are the main factors of human health and economic development (Duan *et al.* 2020; Faouzi *et al.* 2021). Especially when the pump trip happens, it will result in the rapid reduction of flow behind the pump and the sudden change of water velocity in the pipeline (Wylie & Streeter 1993). Water hammer accident causes the significant reduction and increase of water pressure in the pipeline, which seriously endangers the safety of water supply projects (Daude *et al.* 2018). Therefore, many researchers focus on studying and improving the water hammer protection.

For typical water supply projects, many kinds of valves, for instance, air valves, flow regulating valves and the pressure relief valve are generally set in the pipeline to suppress water hammer pressure. It is essential to anticipate and mitigate excessive water hammer surges in the design stage of water supply systems and to define safe operation guidelines of these systems in advance (Ali 2021). In case of a pump trip accident, the backflow can be reduced by closing the valves at the end of the pipeline. If the valve is closed too fast, it will cause the water pressure to fluctuate suddenly and change alternately, resulting in a serious pipe explosion accident. If the valve is closed too slowly, the effect of water hammer protection will be weakened. Therefore, selection and design of the proper characteristics of valves are studied. Additionally, the installation of the valves also plays a vital role in water hammer protection (Kim & Kim 2020). The effect of sudden, linear and stepwise valve closure schemes was analyzed (Yuce & Omer 2019). The opening and closing law of the valves can also affect the protection significantly (Zhang *et al.* 2018). Since the combination of air valves is used in pumping stations normally, the location and the proper number of the air valves impact the effect of water hammer protection significantly. Therefore, the influence of these is studied and compared (Ramezani & Daviau 2021).

Moreover, compared with the traditional reservoir–valve systems, the valve–valve systems are studied numerically by Liu *et al.* (2015). Two valves are installed at the inlet and outlet of the pipe, respectively, and closed with specific time delays. After analyzing the pressure head history and the average velocity history, the results show that in valve–valve systems, the pressure oscillation attenuates obviously. Considering the adverse influence on air supplement by air valves, the air vacuum valves are designed. The vacuum breaking valve (VBV) is a special air valve, which is characterized in such a way that the operating pressure of the VBV can be set below the atmospheric pressure to ensure that it does not work under a certain negative pressure. According to the influence of transient response in the system, the location and its characteristics are analyzed (Ramezani & Karney 2017). A combination of vacuum relief and air release valve is studied in order to avoid column separation and rejoinder water hammer. After analysis of the different diameter sizes and discharge coefficients of these combined protective devices, the results indicate that the smaller diameter size and the air release discharge are more suitable for water hammer protection (Wang & Wang 2019).

Except for different kinds of valves, there are many other protective devices such as air vessel and one-way surge tower. To optimize water hammer protective schemes, the types and locations of air-inlet valves and the size of the air vessels are determined and analyzed (Moghaddas *et al.* 2017). The proposed model is capable to determine the proper number of air-inlet valves and the location to improve the effect of water hammer protection. To save cost on protective investment, the combination of air valves and air vessel schemes is proposed by Miao *et al.*(2017) to reduce the volume of air vessels. Additionally, for optimizing the volume of the air vessel, the overpressure relief valve is combined with an air vessel, and its opening and closing law is analyzed to achieve a better protective effect (Lyu *et al.* 2021). To improve the effect of water hammer protection by the one-way surge tower, the influence of impedance hole diameter ratio on the effect of protection is analyzed, and the reasonable value range of impedance hole diameter ratio is given as a reference (Chen *et al.* 2021). Furthermore, besides considering the effect of the protective devices, the cost of the water hammer protective investment is also important. The multi-device protective approach can reach nearly 30% cost-saving with a better level of safety against cavitation (Yazdi *et al.* 2019).

In this paper, the special terrain, a special siphon breaking structure, which is set at the end of the pipeline, is mainly discussed. In case of a pump trip accident, the water flow between the pipeline and the downstream outlet pool can be quickly cut off to stop the backflow from flowing back to the pipeline by this structure. At the same time, this structure can avoid large water hammer pressure caused by the closing valve. The siphon structure outlets impact the operation of the pump station significantly, based on the experimental research (Shomayramov *et al.* 2019). Since the siphon structure can be installed and operated easily, it is widely used in the pumping stations. The siphon-shaped overflow tower is designed as a new type of pressure-suppressing structure used in long water supply systems. Using the characteristics of the siphon structure can guarantee the system's operational stability and safety during the hydraulic transient process (Yu *et al.* 2016). Milan *et al.* (2020) concentrate on the numerical modeling of flow in the discharge objects with the siphon structure and its validation based on the experimental results. Furthermore, in order to increase its efficiency and improve new designs of the outlet structure, the transient characteristics of the pumping station with the structure of vertical siphon axial flow are explored during the start-up and exhaust process. The siphon structure is combined with the VBV protective device and simulated under two starting modes of pre-opening the VBV and keeping the VBV closed. After comparing the results under these two starting modes, the pre-opening VBV effectively avoids instability in the system (Zhang *et al.* 2021).

The above research studies show that for some water supply projects with the siphon breaking structure, the combined protective schemes with different protective devices can achieve the better protective effect. Considering the characteristics of the VBV, it is an appropriate selection to apply it to the siphon structure for water hammer protection. However, the protective range of the VBV is limited, so it needs to be combined with other water hammer protective devices. However, there are few cases of combined protection of the VBV and other water hammer protective devices with the siphon breaking structure at the end of the pipeline. Therefore, based on the characteristics of VBV, air valves and one-way surge tower, the water hammer protective effects are analyzed and compared in a practical water supply project with a siphon breaking structure. The research results can provide a reference and guideline for other water supply projects with similar characteristics.

MATHEMATICAL MODEL

The basic working principle of the VBV is similar to that of the air valve. The main difference is that the initial operating pressure of the air valve is 0 m, while the initial operating pressure of the VBV is −7.5–0 m. The specific value should be set based on the requirement of the project. The initial principle of setting VBV-operating pressure is that the VBV does not work during normal operation; when the pump trip happens, the VBV works immediately.

Figure 1 is the mathematical model of the VBV. Q_{pxi} is the inflow of section i at time t_0, m^3/s; Q_{ppi} is the inflow of section i at time t, m^3/s; Q_i is the outflow of section i at time t_0, m^3/s; Q_{pi} is the outflow of section i at time t, m^3/s; V is the volume of the air in the pipeline, m^3; C^+ and C^- are the method of characteristic equations of water hammer.

The boundary conditions of the VBV can be divided into the following four cases, according to the velocity of air flowing in and out of the VBV:

Air flows in at a subsonic velocity:

$$\vec{m} = C_{in}A_{in}\sqrt{7p_0\rho_0\left[\frac{p}{p_0}\right]^{1.4286} - \left[\frac{p}{p_0}\right]^{1.7143}}, \quad p_0 > p > 0.528p_0 \tag{1}$$

Air flows in at a critical velocity:

$$\vec{m} = C_{in}A_{in}\frac{0.686}{\sqrt{RT_0}}p_0, \quad p \leq 0.528p_0 \tag{2}$$

Air flows out at a subsonic velocity:

$$\vec{m} = -C_{out}A_{out}p\sqrt{\frac{7}{RT}\left[\left(\frac{p_0}{p}\right)^{1.4286} - \left(\frac{p_0}{p}\right)^{1.7143}\right]}, \quad \frac{p_0}{0.528} > p > p_0 \tag{3}$$

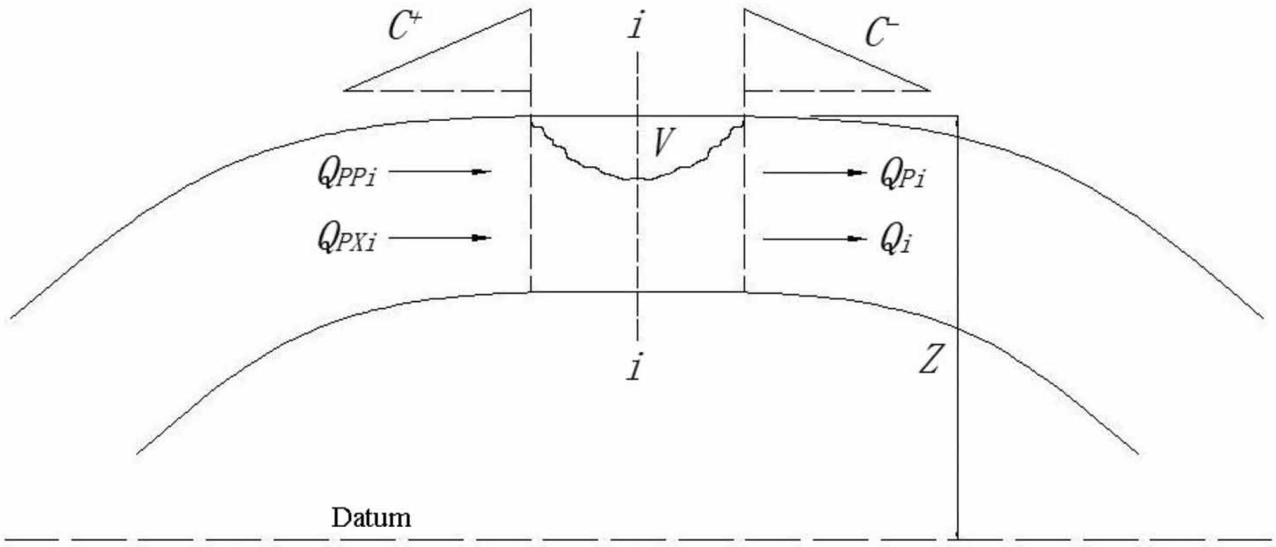

Figure 1 | Mathematical model of the VBV.

Air flows out at a critical velocity:

$$\vec{m} = -C_{out}A_{out}\frac{0.686}{\sqrt{RT_0}}p, \quad p > \frac{p_0}{0.528} \tag{4}$$

where $\vec{m}$ is the air mass flow, kg/s; C_{in} is the inlet flow coefficient of the valve; A_{in} is the inlet flow area of the valve, m^2; R is the molar gas constant, $8.31\mathrm{J}\cdot\mathrm{mol}^{-1}\cdot\mathrm{K}^{-1}$; T and T_0 are the inside and outside temperatures of the pipe, K; ρ_0 is the atmospheric density, kg/m^3; C_{out} is the outlet flow coefficient of the valve; A_{out} is the outlet flow area of the valve, m^2; P is the pressure inside the pipe, m and P_0 is the local atmospheric pressure, m. From Equations (1) to (4), if the pressure at the VBV is lower than the engineering pressure control standard, the inlet diameter of the VBV can be increased whenever air is sucked into the VBV.

When the pressure in the pipeline is higher than the set operating pressure of the VBV or there is no air in the pipeline, the boundary condition at the connection between the VBV and the pipeline is the general internal section solution of the pressure head H_{pi} and flow Q_{pi} at the pipeline node. When the pressure in the pipeline is less than the set operating pressure of the VBV, the VBV opens instantly and air flows in. Therefore, before the air is discharged, it can be assumed that the gas satisfies the ideal gas equation:

$$pV = \frac{m}{M}RT \tag{5}$$

where m is the air mass, and M is the molar mass of gas, kg/mol.

The relation of $H_p$and p is as follows:

$$H_p = \frac{p}{\gamma} + Z - H_a \tag{6}$$

where H_p is the pressure head of the pipeline node, m; γ is the liquid bulk density, kN/m^3; Z is the elevation of the VBV position, m and H_a is the atmospheric head (absolute head), m.

Approximate the difference of Equation (5) and combine with Equations (1)–(4), and then substitute it into Equation (6), the equation can be written as follows:

$$p\left\{V_0 + 0.5\Delta t\left[Q_i - Q_{pxi} - \left(\frac{C_{P1}}{B_{P1}} + \frac{C_{M2}}{B_{M2}}\right) + \left(\frac{1}{B_{P1}} + \frac{1}{B_{M2}}\right)\left(\frac{P}{\gamma} + Z - H_a\right)\right]\right\} = [m_0 + 0.5\Delta t(\overrightarrow{m_0} + \vec{m})]RT \tag{7}$$

where V_0 is the initial hole volume, m^3; Δt is the time increment, s; Q_i is the outlet flow of section i at time t_0, m^3/s; Q_{pxi} is the inlet flow of section i at time t_0, m^3/s; C_{P1}, C_{M2}, B_{P1} and B_{M2} are the state quantities related to the previous time t_0 in the characteristic compatibility equation of water hammer; m_0 is the mass of air at t_0, kg; $\overrightarrow{m_0}$ is the flow of the air flowing in and out of the hole at time t_0, kg/s and $\vec{m}$ is the flow of air flowing in and out of the hole at time t, kg/s.

The above equation is about the air hole generated at the time t. In the equation, all the parameters are known except p.

Feasibility analysis

For the water supply systems with the siphon breaking structure, the VBV is generally installed at the top of the siphon pipe. When the system operates stably, the negative pressure within the allowable range is allowed at the siphon structure. When the pump trip happens, the pressure at the siphon structure quickly drops below the operating pressure of the VBV, and then the VBV starts to intake air. Since the elevation of the siphon pipe bottom is higher than that of the outlet pool, the siphon structure quickly stops the water from flowing to the outlet pool, and stops water from flowing back to the pipeline. Compared with the normal water supply project, this system avoids the problem of large flow and high velocity caused by the closing valve. However, the siphon structure with the VBV system is limited in the range of water hammer protection. This structure can prevent water from flowing back to the pipeline, but it is hard to suppress the water hammer in front of the pipeline. Making use of characteristics of the siphon structure, two protective devices (air valves and one-way surge tower) are combined with the VBV, respectively, in order to meet water hammer protective standards.

Air valve is a common protective device, which is normally installed at a high point along the pipeline to allow for air intake and exhaust. Thus, in this paper, three air valves are installed and combined with the VBV based on the siphon structure. However, the effect of this combined water hammer protection is not satisfied with the standards. Due to the repeated intake and exhaust of the air valves, the pressure oscillation will be aggravated. Thereby the water hammer protection will be affected seriously. Moreover, according to the characteristic of the air valve, much gas will be sucked into the pipe, which endangers the safety of the pipe.

To avoid the problems discussed above, the combination of the one-way surge tower and the VBV protective scheme is proposed based on the siphon structure. The layout of the water supply system with the siphon structure in VBV and one-way surge tower combined protection is shown in Figure 2.

The one-way surge tower is set at the high position behind the pump, and the VBV is installed at the top of the siphon pipe. When the pump trip happens, the flow behind the pump decreases sharply and generates a large pressure drop wave. When the pressure drop wave transmits to the position of the one-way surge tower, since the pressure inside the tower is larger than

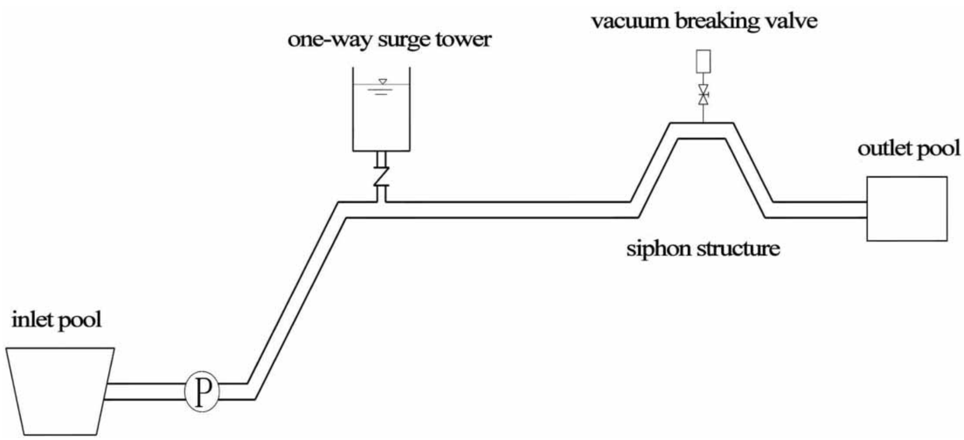

Figure 2 | Layout of the water supply system with the siphon structure in the VBV and one-way surge tower scheme.

that at the bottom pipe, the check valve opens instantly and the one-way surge tower starts to supplement water, so as to suppress the negative pressure, and avoid water column separation happening. In the siphon structure section, the pressure drops to −2.0 m (VBV-operated pressure) and the VBV opens to inlet the air in order to avoid the outlet pool water from flowing back to the pipe. This combined protective scheme can avoid the intake of too much gas in the pipe, and the protective process of the one-way surge tower will not affect the VBV operating in the siphon structure.

Case study

The characteristics of the practical water supply system studied in this paper are small pump head, large flow, short pipeline length and large pipe diameter. The total length of the pipeline is 947 m, the material of the pipeline is DN3240 steel pipe and the design water supply flow is 45 m^3/s. The design water level of the inlet pool is 218.50 m, and the design water level of the outlet pool is 261.22 m. Four single pumps with a 13.3 m^3/s design flow and a 45 m design head are installed in the pump station. The elevation line of the pipe center and the piezometric headline of the pipe under stable conditions are shown in Figure 3. The elevation of the pipe center at the outlet of the pipeline is 263.70 m, and the piezometric head is 263.45 m, forming a typical siphon structure.

System without any protective scheme

Suppose the water supply system is without any water hammer protective scheme. When the pump trip happens, the minimum pressure enveloping line along the pipeline and variation pressure and flow after pump are shown in Figure 4.

It can be seen from Figure 4 that due to the large flow of the water supply project, the system flow changes greatly when the pump trip happens, which results in a rapid pressure drop of about 42.27 m behind the pump. Basically, the pressure drop wave will propagate behind the pump, so that the minimum pressure in the pipe center at stake no. K0 + 135.90 will reach −24.16 m, and the minimum pressure of more than half of the pipeline will be lower than the vaporization pressure (−10 m). It indicates that if there is no water hammer protective scheme, the accident of liquid column separation and gas column bridging occurs in the pipeline, which will seriously endanger the safety of the pipeline.

When the pump trip happens, the water supply system is required to meet the protection standards, which are when the minimum pressure of the pipeline is not less than −5m under the protection of the VBV and air valves, the minimum pressure

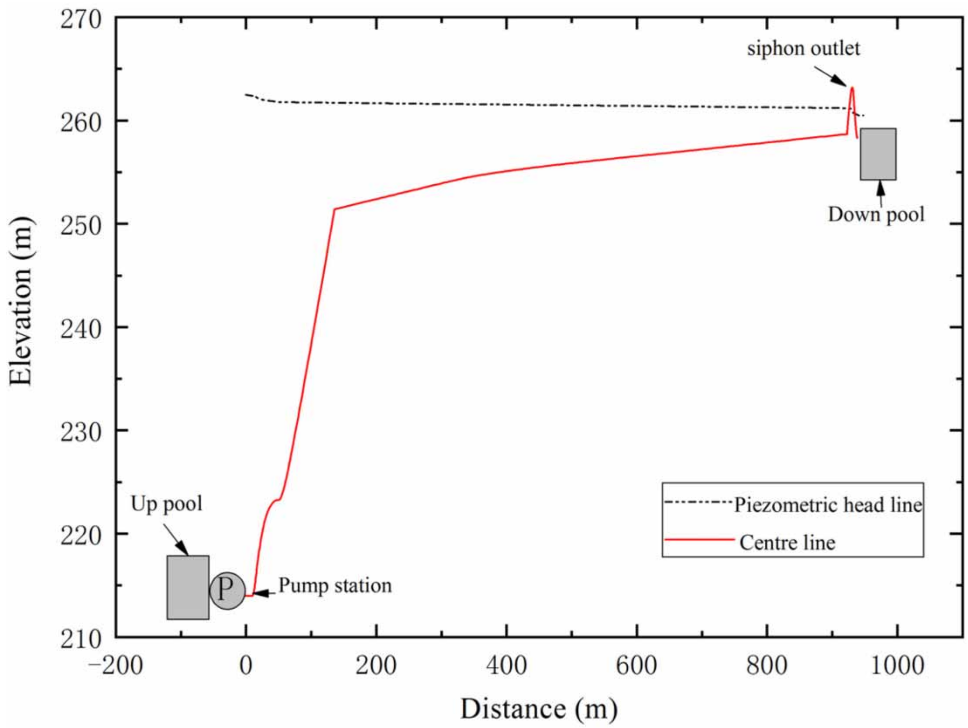

Figure 3 | Pipe centerline, piezometric headline and schematic diagram of the water supply project.

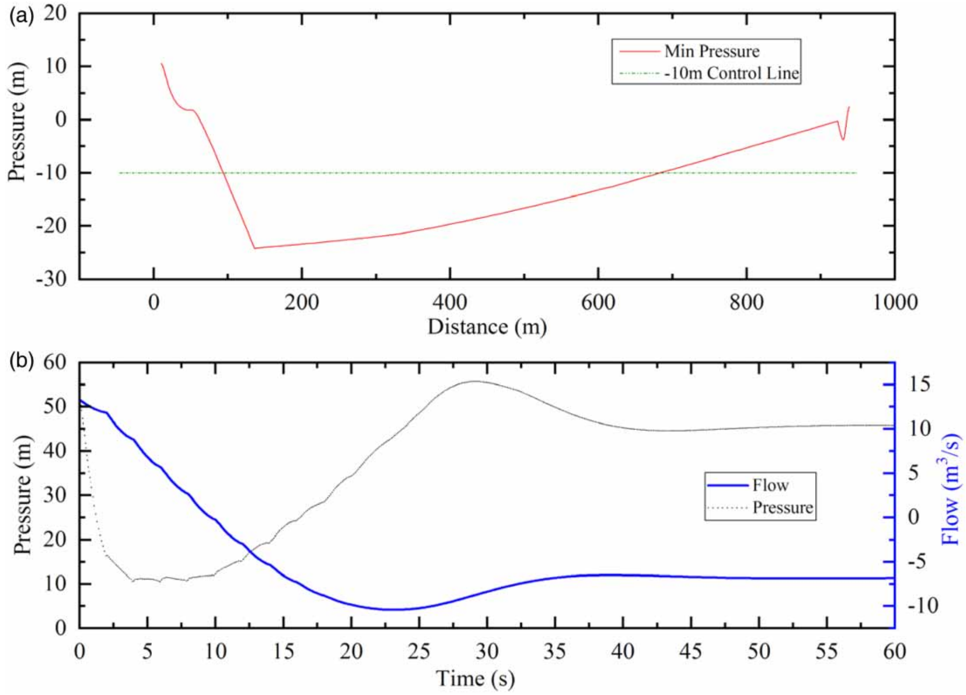

Figure 4 | (a) Minimum pressure enveloping curves without any protection and (b) variation pressure and flow after pump when pump trip happens.

of the pipeline is not to be negative under the protection of VBV and one-way surge tower. The length of the whole pipeline is short, the water hammer pressure flowing back to the pump for the first time is less than the maximum positive pressure standard; thus in this practical water supply project, the negative pressure caused by the pump trip needs to be mainly protected.

System with the single VBV scheme

To ensure that the water supply system can operate stably and safely, when the pump trip happens, the pressure along the pipeline will be larger than the vaporization pressure (−10 m) of water. The setting principle of the VBV-operating pressure shall be less than the stable pressure at this point to ensure that the VBV does not work during the stable operation of the system. The operating pressure value shall also be greater than the minimum pressure at this point or the vaporization pressure of water to ensure that the VBV can be opened instantly when the pump trip happens. Thus, based on the condition of this water supply project, the VBV is installed separately at the siphon structure (stake no. K0 + 930.25), and the initial operating pressure of the VBV is −2 m. The simulation results of the system under the accident of pump trip are shown in Figure 5.

It can be seen from Figure 5 that the pipeline with more than two-thirds of length does not meet the minimum pressure control requirements of the pipeline. Theoretically, the minimum pressure of some pipe sections behind the pump is lower than the vaporization pressure of water. Thus, water column separation will occur in this section of the pipeline, endangering the safety of the pipeline system. Obviously, after the pump trip happens about 15 s, the VBV finishes air supplement, and flow tends to be stable. The siphon structure at the end of the pipeline works together with the VBV to quickly and effectively cut off the flow between the pipeline and the outlet pool. However, the VBV can only protect the siphon section to meet the protective standard. Thus, this structure with the VBV system needs to be combined with other protective devices.

System with the VBV and air valve scheme

The air valve is a common water hammer protective device in a water supply project. According to the theoretical analysis of the air valve, three DN400 air valves are set at stake nos K0 + 136, K0 + 379 and K0 + 619 in the system pipeline, numbered 1, 2 and 3, respectively. DN800 VBV is set at the siphon structure (stake no. K0 + 930.25) for water hammer protection. The simulation results of the water supply system under the accident of the pump trip are shown in Table 1 and Figure 6.

In Table 1, it is obvious that when a pump trip happens, a large amount of air intakes by first two air valves, and the pressure in the pipeline after the pump fluctuates wildly under the protection of VBV and air valves. From Figure 6, the

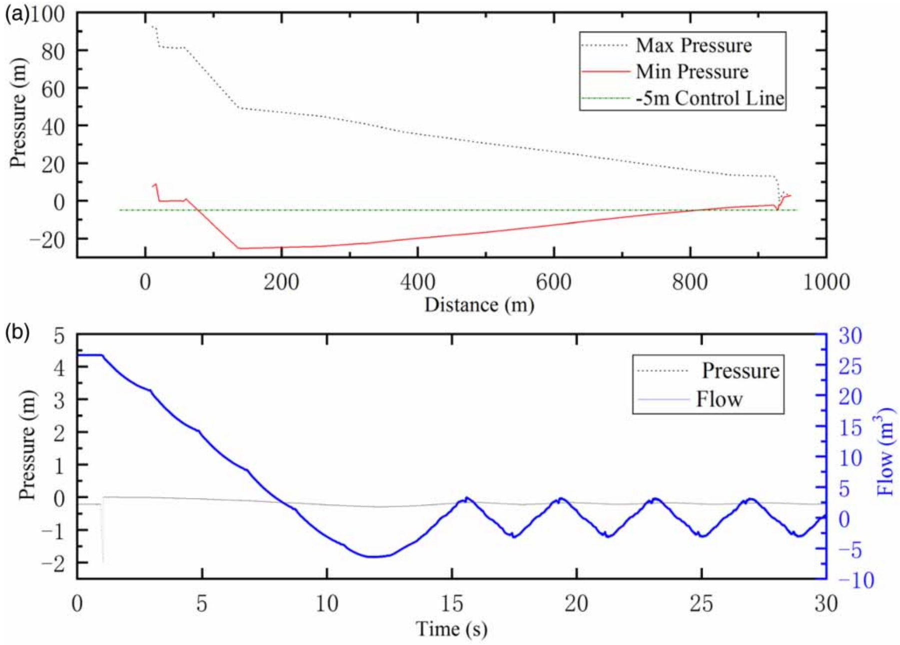

Figure 5 | (a) Enveloping curves of minimum pressure in the single VBV method and (b) variation pressure and flow at the siphon structure.

Table 1 | Maximum air intake of the air valve

Number of air valves	**1**	**2**	**3**
Maximum air intake (m^3)	201.96	92.49	0.17

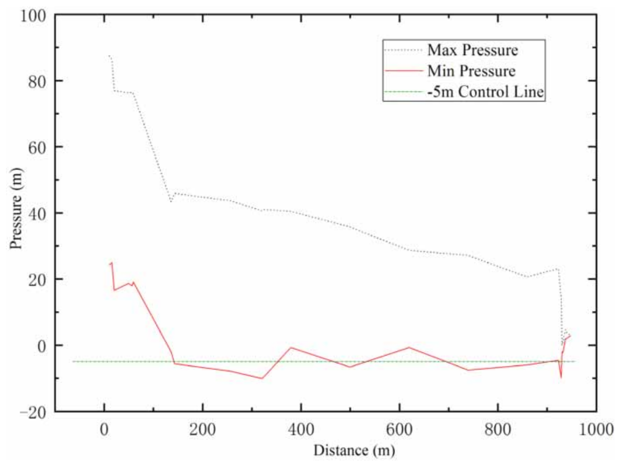

Figure 6 | Enveloping curves of minimum pressure in the VBV and air valve method.

negative pressure values along the pipeline are large, which cannot meet the requirements of water hammer pressure control standards, and the system may be seriously damaged. After the pump trip happens, due to the large pressure drop after the pump, when the pressure wave transmits to the installed air valve's position, a large amount of air is sucked into the pipeline by the air valve. With the increase of the pressure in the pipe, the air valves begin to exhaust, and the flow of the gas in the exhaust process is often large, which results in the gas column bridging at the end of the exhaust process (about 140 s). The gas column bridging will generate high pressure. After the high pressure is reflected by the valve and the upstream pool, a large negative pressure will be generated. The repeated inlet and exhaust of the air valves will aggravate the pressure oscillation, affecting the water hammer protection.

System with the VBV and one-way surge tower scheme

The air valve suppresses the pressure by air supplement. For the hydraulic transition process, too much gas in the pipeline is extremely dangerous to pipeline safety, while the one-way surge tower ensures pipeline safety by water supplement. That is why the VBV and one-way surge tower combined protective scheme is proposed in this paper. The one-way surge tower is set at the local high point after the pump (stake no. K0 + 143) and works with the VBV at the siphon structure. The shape parameters of the one-way surge tower are shown in Table 2, and the numerical simulation results based on the method of characteristic equations are shown in Figure 7.

It can be seen from Figure 7 that the combined protection of VBV and one-way surge tower after the pump effectively ensures the safety of the operation system. After the pump trip happens about 33 s, the one-way surge tower finishes water supplement and the pressure tends to be stable. The maximum pressure along the pipeline appears at the valve position after the pump, and the maximum pressure is 59.11 m, which meets the requirements of the pipeline pressure standard. The minimum pressure of the pipeline except for the siphon structure section is 0.55 m, which meets the negative pressure control standard in the pipeline. Since the VBV is installed at the siphon structure, when the pump trip happens, the pressure drop wave quickly transmits to the siphon structure section. When the pressure drops to −2.0 m (VBV-operated pressure), the VBV opens to inlet the air, so as to stop the water from flowing to the outlet pool. The minimum pressure in this section is −2.28 m, which meets the minimum pressure control requirement (not less than −5 m).

Table 2 | Shape parameters of the one-way surge tower

Check valve diameter (m)	Cross-sectional area (m^2)	Top elevation (m)	Initial water level (m)	Lowest water level (m)	Bottom elevation (m)
2.2	60.0	264.0	263.5	255.5	255.0

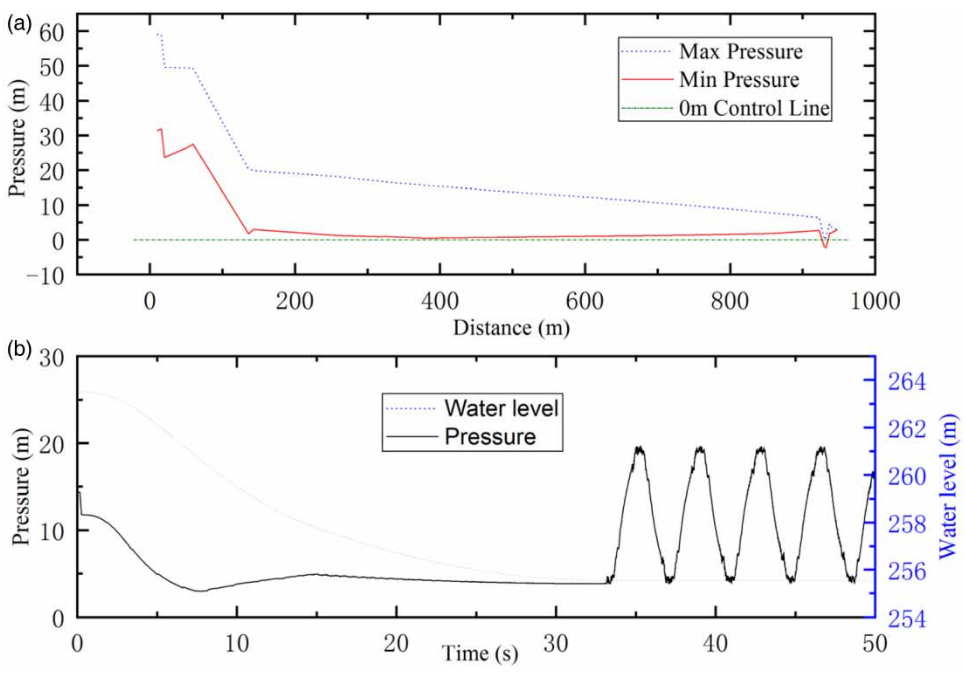

Figure 7 | (a) Enveloping curves of minimum pressure in the VBV and one-way surge tower scheme. (b) Variation process of bottom pressure and water level in the one-way surge tower.

DISCUSSION AND ANALYSIS

In Figure 8, it is evident that in the single VBV protective method, theoretically the minimum pressure of the pipeline can reach −25 m, which is far lower than the vaporization pressure of water of −10 m. This may cause gas column bridging and seriously endanger the safety of the project. This is because the elevation of the pipeline in this section is high, the initial internal water pressure is small and there is no effective supplementary pressure protective measure. When the pressure drop wave after the pump transmits here, it generates a large negative pressure in the pipeline. When the pressure drop wave transmits to the siphon section, the pressure at the VBV position suddenly decreases from the stable operating pressure of −0.22 to −2.0 m (operated pressure of the VBV), and then the VBV opens quickly to intake air, and the flow of pipeline drops sharply. When the pump trip happens about 15 s, the air supplement by the VBV is completed, and the pipeline pressure and flow are stable, which can require the minimum pressure control standards of the pipeline only in the siphon section. In the combined protective method of the VBV and air valves, the minimum pressure of the pipeline is −9.94 m. The protective effect of the siphon structure is worse than the only VBV protective scheme. Due to the alternating change of water pressure in the pipeline during the hydraulic transition process, a large amount of gas in the pipeline will be repeatedly sucked and discharged by the air valves, resulting in the gas column bridging. The high pressure generated by the gas column bridging phenomenon will form a large negative pressure after being reflected by the valve and the high-level pool. The pressure oscillation caused by air valves affects the VBV protection at the siphon structure. Thus, to avoid too much gas mixing into the pipeline, using water instead of gas to supplement pressure is more safe and appropriate. In the combined protective method of VBV and one-way surge tower, the pressure of the pipeline can completely meet the water hammer protective requirements, which can effectively ensure the safety of the project. After the pump trip happens, due to the kinetic energy of the water in the pipeline, the water still flows through the siphon structure to the outlet pool. The one-way surge tower decreases the pressure drop in the front of the pipeline supplementing water. After the pump trip happens at about 33 s, the one-way surge tower finishes water supplement, the water pressure in the pipeline tends to be stable and the maximum water level of the pipeline is no longer greater than that of the pipe bottom at the siphon section. At this moment, the siphon structure stops the water from flowing to the outlet pool. The kinetic energy of the water is completely transformed into potential energy. The one-way surge tower completes the water supplement to the pipeline, and the check valve is closed. For this special pipeline, the combined scheme of VBV and one-way surge tower can effectively suppress the water hammer pressure. The one-way

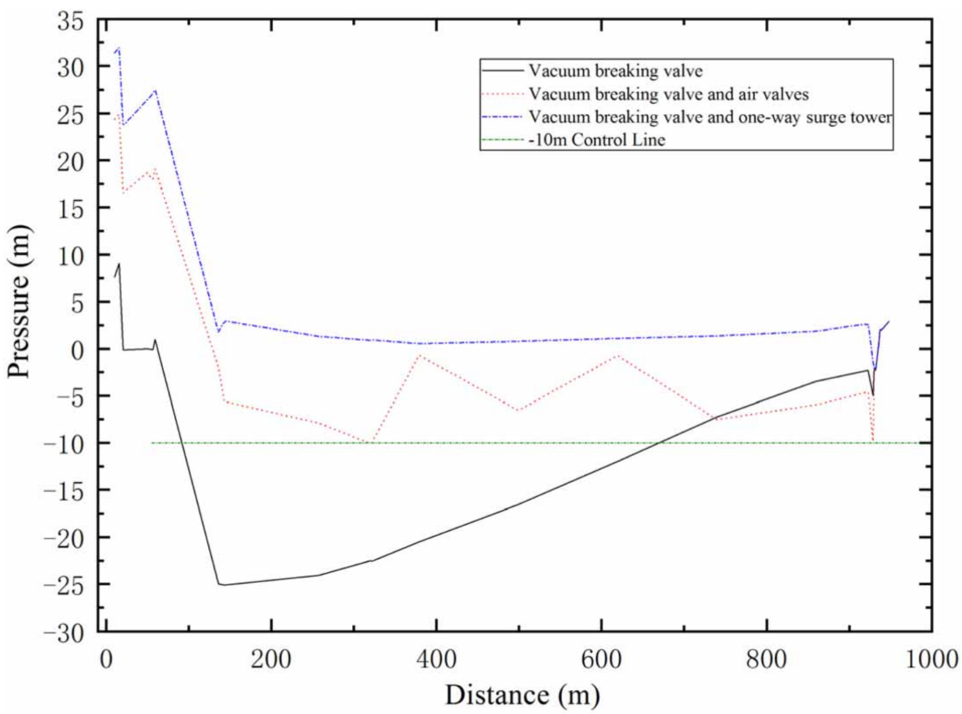

Figure 8 | Enveloping curves of minimum pressure in different protective schemes.

surge tower works on the front of the pipeline to supplement water and pressure, and the VBV works together with the siphon structure on the back of the pipeline to supplement air and pressure. The water and gas are separated by the siphon structure, which prevents the water from mixing with the gas in the pipeline, and avoids the gas column bridging happening. Therefore, this combined scheme of VBV and one-way surge tower effectively ensures the safety of the pipeline.

CONCLUSION

This paper analyzes the characteristics of the water supply system with the siphon breaking structure at the end of the pipeline. Based on the method of characteristic equations, the working principle and mathematical model of the VBV are briefly described, and the operation of the VBV setting at the siphon structure is analyzed. Based on the requirements of the pressure control standards, the protective effects of three schemes (the single VBV protection, the combined protection of the VBV and the air valves, and the combined protection of the VBV and one-way surge tower) are analyzed and compared. The results show that the VBV installed at the siphon section positively affects the stable operation and water hammer protection. It can cooperate with the siphon structure to quickly and effectively cut off the water flow between the pipeline and the outlet pool. However, the siphon structure with the VBV system is limited in the range of protection. It only can meet the pressure control standards at the siphon structure section. Therefore, the water hammer protection of the whole pipeline system should be combined with other water hammer protective devices.

In the combined water hammer protective scheme of the VBV and air valves, when the valve after the pump is closed, a large amount of water impacts the air valves, which will accelerate the exhaust speed of the air valves and the pressure generated by the gas column bridging is too large. The pressure oscillations are obviously caused by the repeated inlet and exhaust of the air valves. This will result in a bad effect on the protection of both positive and negative pressures of the pipeline. Too much gas mixed in the water will endanger the safety of operation. In the combined protective scheme of VBV and one-way surge tower, the VBV supplements pressure by gas, while the one-way surge tower supplements pressure by water. Additionally, the siphon structure can prevent the water from mixing with gas in the pipeline, so as to avoid the phenomenon of gas column bridging. Therefore, the combined scheme of VBV and one-way surge tower effectively ensures the safety of the pipeline.

DATA AVAILABILITY STATEMENT

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

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