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Air valve arrangement criteria for preventing secondary pipe bursts in long-distance gravitational water supply systems

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ABSTRACT

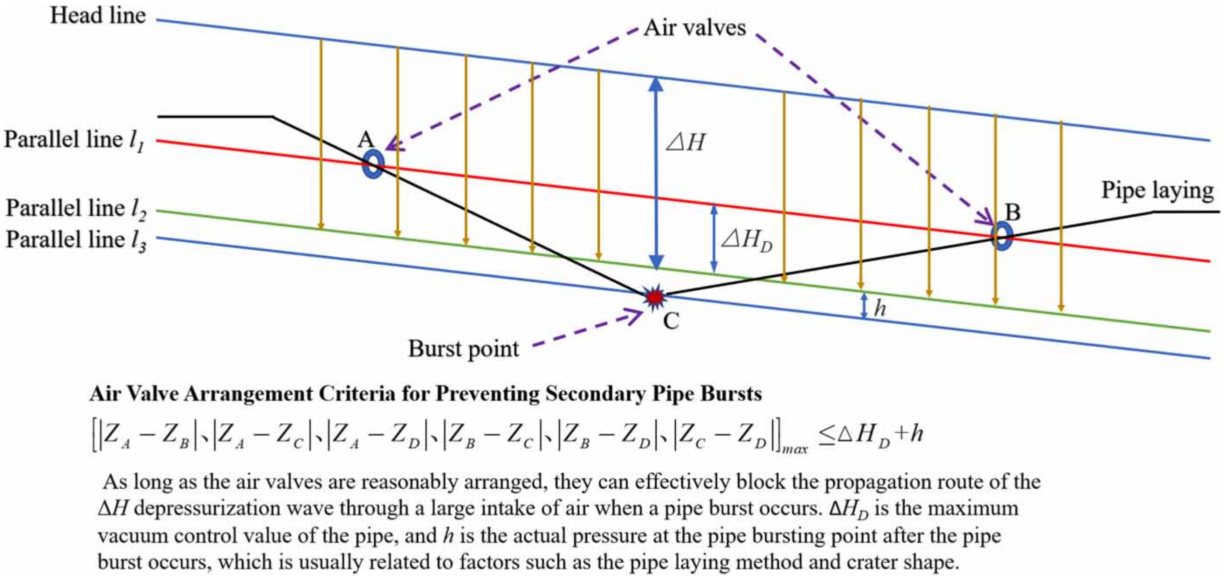
Pipe burst incidents in long-distance gravitational water supply systems (LGWSSs) result in hydraulic characteristic variations and pose significant challenges. This study aims to prevent secondary pipe bursts by addressing the propagation of water hammer waves triggered by primary pipe bursts. Based on an analysis of pipe burst incidents and considering different pipe laying methods, air valve arrangement criteria are developed to mitigate the risk of secondary bursts in LGWSS pipelines. The principal results include a reasonable mathematical analysis model for understanding pipe bursts and the determination of air valve arrangement criteria which considers potentially dangerous pressure variations resulting from primary pipe bursts. This model aims to mitigate the adverse effects of pipe bursts and minimize the likelihood of secondary bursts. Implementing the proposed criteria has important engineering applications, thus improving the reasonable and effective placement of air valves to prevent secondary pipe bursts in LGWSSs. The conclusion involves optimizing the placement of air valves to enhance the flexibility and reliability of LGWSSs. By implementing the proposed air valve arrangement criteria, water supply systems can minimize the potential damage caused by pipe bursts and improve overall operational efficiency.

Key words: air valve, gravity flow water supply, layout theory, long-distance water supply, pipe burst, water hammer protection

HIGHLIGHTS

- The traditional arrangement of air valves with a certain distance apart cannot effectively prevent the secondary tube explosion in the long-distance gravity flow water supply project.
- This paper obtained the installation elevation requirements of air valves that can effectively prevent the secondary tube explosion in the long-distance gravity flow water supply project.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water hammer incidents in water supply systems pose a significant challenge, leading to hydraulic characteristic variations and potential secondary pipe bursts. Previous research has primarily focused on analyzing valve operations and transient local blockages to prevent primary pipe bursts. However, the negative pressure water hammer following a pipe burst has received less attention, despite its potential to cause additional damage and increase the risk of secondary bursts.

Secondary pipe burst prevention and air valve arrangement in long-distance water supply projects have been topics of interest in hydraulic engineering. Previous studies have investigated various methods to simulate water hammers, analyze their effects on pipelines, and detect pipe bursts and blockages. For example, Liu *et al.* (2011) explored explicit–implicit coupling methods for water hammer simulations, while Wu *et al.* (2015) studied pressure transients during pipeline filling caused by air valve closure. These studies highlighted the importance of understanding water hammer phenomena and the role of air valves in preventing pipe bursts. Moreover, researchers have examined the effects of different pipeline components, including air valves, on water hammer pressures and optimal positioning. Li *et al.* (2015) investigated the effects of air valves on water hammer pressures in LGWSSs. Hu *et al.* (2007) developed a mathematical model for air valves based on real gas characteristics, providing insights into the behavior of air valves and their impact on water supply systems. Fuertes-Miquel *et al.* (2016) and Moghaddas *et al.* (2017) conducted research on optimizing transient protection in pipelines using air valves, aiming to enhance the system's resilience against hydraulic transients. Their findings have contributed to the proper arrangement and operations of air valves in relevant projects.

In the context of secondary pipe burst prevention, Ramezani *et al.* (2015) presented a selective critical literature review addressing the challenges associated with air valves, providing a comprehensive overview of research in this area. Duan (2020) developed a transient frequency response-based method for simultaneous leakage detection and partial blockage identification in water supply pipelines. Zhang *et al.* (2011) investigated the use of transient pressure-damping methods for pipe burst detection, localization, and quantification. These studies emphasized the importance of prompt detection and localization of pipe bursts to minimize potential secondary damage. Dong (2013) focused on the study of valve-closure water hammer in a gravity pressured water-delivery system with a branch line, Chen *et al.* (2021) investigated the optimization of impedance size in a oneway surge tank within a long-distance water supply system, aiming to improve the system's hydraulic performance and transient protection capabilities. The study by Alanazi *et al.* (2022) examined the performance of buried pipelines subjected to static loads, considering different materials and soil types. These findings provide valuable insights for ensuring the safety and integrity of buried pipelines in long-distance water supply projects. Adeyanju & Manohar (2022) investigated the performance of a cross-flow turbine at different flow rates and guide vane angles and provided insights for the optimization of turbine efficiency in long-distance water supply projects. Nogmov *et al.* (2023) developed a flow-measuring hydropneumatic bench to test pipeline valves, enhance testing capabilities and reduce costs, thereby contributing to the safe and reliable operation of pipelines in secondary pipe burst prevention and air valve arrangement.

Balacco *et al.* (2015) focused on the investigation of the behavior of air valves during hydraulic transients. This study provided valuable insights into the behavior of air valves that can contribute to the design and operation of hydraulic systems. Yang & Shi (2005) focused on controlling pipeline hydraulic transients in the south to north water transfer project, aiming to improve the system's stability and reliability during water transfer operations. Chen *et al.* (2022) conducted a study on the joint protection of air tanks and air valves in long-distance water supply systems to enhance the system's resilience against water hammer and pressure surges. Wang *et al.* (2019) investigated the impact of multi-valve closure on superposed pressure in a tree-type long-distance gravitational water supply system, providing insights into pressure management techniques. Coronado-Hernandez *et al.* (2017) analyzed the performance of different air valves in a water-emptying pipeline. Experiments and numerical simulations were conducted to compare the behavior and efficiency of various air valves in releasing air during the emptying process. The study provided practical information on the selection and optimization of air valves in water pipelines.

In summary, previous studies highlighted the importance of secondary pipe burst prevention and air valve arrangement in long-distance water supply projects. By studying water hammer simulations, pipe burst detection methods, and the effects of pipeline components, researchers contributed to the improvement of the overall safety and integrity of water supply systems. However, pipe explosions in water supply engineering are extremely random and can be caused by various factors, including (but not limited to) aging pipelines, improper installation or maintenance, external damage, pressure fluctuations, sudden changes in flow rate, and unexpected events, such as earthquakes or natural disasters. Once a water supply accident occurs, it can have serious consequences in terms of direct and secondary damages. Although direct damage from an explosion cannot be avoided, potential secondary damage, such as a series of explosions that could be triggered by the initial accident, can be minimized by formulating appropriate measures. These incidents result in hydraulic characteristic variations and can have detrimental effects on the operation and reliability of water supply networks. The consequences of pipe bursts include disruption of water supply, potential damage to infrastructure, and increased operational costs. Therefore, it is crucial to address the underlying causes and develop effective measures to prevent secondary pipe bursts. Secondary pipe burst prevention is critical to ensure the overall safety and integrity of a project.

Therefore, we developed general criteria for the elevation arrangement of air valves in LGWSSs to prevent secondary pipe bursts in this study. For this purpose, we examined the unsteady flow in an underground buried pipe subject to a pipe burst and assessed the significance of the air valve elevation arrangement. We also established a new mathematical model for air valves based on van der Waals forces. One of the key innovations of this research is the development of air valve arrangement criteria specifically tailored to prevent secondary pipe bursts in LGWSS pipelines. By analyzing pipe burst incidents using different pipe laying methods and considering the dangerous pressure variations caused by primary pipe bursts, the study establishes guidelines for the reasonable and effective placement of air valves. Our proposed criteria may be useful for determining a reasonable layout of air valves and identifying whether the air valve arrangement scheme can effectively prevent secondary pipe bursts in LGWSSs.

2. MATHEMATICAL MODEL AND PRINCIPLES

The characteristic line method used in this study is extensively used for solving hyperbolic partial differential equations, such as continuity and motion equations in hydraulic transient analysis. It is particularly relevant in the study of the dynamic behavior of fluid flow in pipelines during transient events, such as pipe bursts. By utilizing characteristic lines, which represent the paths along which information flows in the system, this method enables a systematic analysis of pressure and flow variations over time.

One of the key advantages associated with the use of the characteristic line method in this study is its capability to transform partial differential equations into characteristic compatibility equations. This transformation simplifies the calculation process and facilitates the determination of pressure and flow parameters at the burst point. Additionally, the method allows for efficient computation of the transient behavior of the hydraulic system along the pipeline, considering the spatial and temporal variations of the flow variables. In our mathematical model, the characteristic line method is applied to solve the continuity and motion equations governing the hydraulic transient of the pressure pipeline. By transforming these equations into characteristic compatibility equations, we can derive a set of equations that relate the pressures and flow rates at different locations along the pipeline. These equations, in conjunction with known quantities at previous moments, are utilized to calculate the pressure and flow parameters at the burst locations, thus enabling the analysis of the pipe burst process. The characteristic line method offers enhanced accuracy and reliability in capturing the transient behavior of the hydraulic system. It takes into account essential factors, such as wave propagation speed, friction coefficient, and pipe diameter. By considering these factors, the method provides more accurate results compared with simplified models or methods that neglect these complexities. Consequently, the characteristic line method enables a more comprehensive understanding of the pressure and flow variations during pipe burst events.

The mathematical model presented by Wylie and Streeter in the 1970s was applied in this study; it is based on several basic assumptions:

1. Air enters and leaves the pipe through the valve under isentropic flow conditions as a perfect gas.
2. The volume variation of air in the pipe follows the isothermal law of a perfect gas.
3. The air entering the pipe remains near the valve, from where it can be expelled.
4. The elevation of the liquid surface remains relatively constant, and the volume of air is small compared to the liquid volume of the pipeline reach.

When the pipe bursts, the pressure at the burst point rapidly drops to the local atmospheric pressure, resulting in an instantaneous water hammer pressure drop wave. In practical engineering, the instantaneous pressure drop at the burst point can be approximated as a direct negative water hammer because the burst time is very short. In fact, the pressure change at the burst point is affected by multiple factors, such as the size of the orifice area, local head loss at the burst point, and elevation at the burst point. The process is relatively complex. The burst pipe can be approximated as a process of rapid opening and discharge of a virtual valve, and the existing mathematical model can be used for approximate simulation calculation. The mathematical model of the burst pipe is shown in Figure 1.

The continuity equation and motion equation of hydraulic transient of pressure pipeline can be expressed as

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

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

where x is the length along the center line of the tube, m; t is time variable, s; H is the piezometric head of the pressure pipe, m; v is the flow velocity in the pipe, m/s; λ is the Darcy–Weissbach friction coefficient of the pipeline; D is the inner diameter of the pipe, m; θ is the acute angle between the pipe center line and the horizontal plane; a is the water hammer wave propagation speed, m/s; and g is the acceleration of gravity, m³/s.

Equations (1) and (2) can be simplified as a standard hyperbolic partial differential equation, which can be transformed into characteristic compatibility equation of pipe water hammer calculation by the characteristic line method. The compatibility

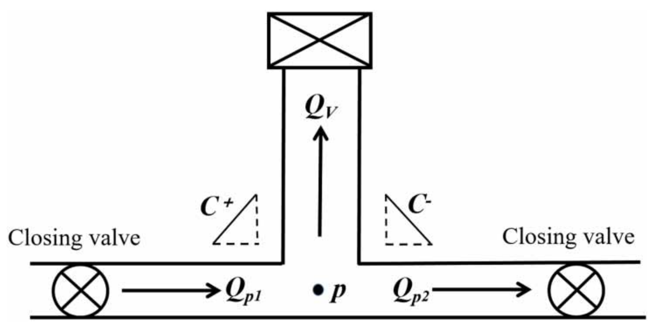


Figure 1 | Mathematical model of pipe burst.

equations of P points are as follows:

$$H_P = C_{P1} - B_{P1}Q_{P1} \tag{3}$$

$$H_P = C_{M1} + B_{M2}Q_{P2} \tag{4}$$

where H_P is the internal water pressure of point P (the burst point at the center line), m; C_{P1}, B_{P2}, C_{M1}, and B_{M2} are the known quantities at the previous moment; Q_{P1} is the flow rate before the valve, m^2/s; and Q_{P2} is the flow rate before the valve, m^2/s.

The continuity equation of flow can be expressed as

$$Q_{P1} = Q_V + Q_{P2} \tag{5}$$

where Q_V is the discharge of P point after the explosion, m^3/s.

The pressure at the burst point satisfies

$$H_P = Z_P + \Delta h_V = Z_P + \alpha_V Q_V^2 \tag{6}$$

where Δh_V is the local head loss at the burst point, m, and α_V is the local water loss coefficient at the burst point, s^2/m^5.

The overcurrent of the virtual valve can be described as

$$Q_V = C_d A_V \sqrt{2g(H_P - H_a)} \tag{7}$$

where C_d is the flow coefficient of the pipe burst point equivalent to the virtual valve, depending on the actual situation of the pipe burst, m^2; H_a is the ambient atmospheric pressure outside the burst point, m; and A_V is the flow cross-sectional area, m^2.

Set $R_k = 1/2gC_d^2A_V^2$, and combine this equation with Equations (1)–(7) to obtain

$$Q_V = \frac{-1 + \sqrt{1 - 4\left(\frac{1}{B_{P1}} + \frac{1}{B_{M1}}\right)R_k\left[\left(\frac{1}{B_{P1}} + \frac{1}{B_{M1}}\right)(H_P - H_a) - \left(\frac{C_{P1}}{B_{P1}} + \frac{C_{M1}}{B_{M1}}\right)\right]}}{2\left(\frac{1}{B_{P1}} + \frac{1}{B_{M1}}\right)R_k}. \tag{8}$$

Equation (6) is the solution equation for the leakage at the burst pipe. After Q_V is obtained, other parameters can be substituted into the corresponding equation. Using Equations (1)–(8) and the corresponding relations shown in Figure 1, the changing process of pipe flow and water head under load disturbance of elastic model can be calculated.

When the water conveyance system is in normal operation, the virtual valve remains closed: when a pipe burst accident occurs at point P, the virtual valve opens quickly, and the water in the system gushes out in large quantities. The pressure at the pipe burst point drops rapidly, and in extreme cases, it will drop to atmospheric pressure. In order to make use of the existing facilities and reduce the additional investment, the overhaul butterfly valve arranged along the pipeline is generally used as the isolating valve after the pipe burst, which is closed together with the regulating valves of the pipeline, so as to isolate the pipe section of the burst pipe. The resulting water hammer depressurization wave propagates forward and backward along the pipeline from the explosion point. The greater the original working pressure at the explosion point, the greater the water hammer depressurization wave generated. Due to the uneven laying of the pipeline, the water flow at the lower working pressure point in the pipeline may vaporize during the process of propagation of the pressure drop wave. It then produces a severe bridging water hammer, resulting in a secondary explosion in the pipeline and negative pressure damage. Consequently, the negative pressure should be prevented first after the pipe explosion. Therefore, it is very important to clarify whether the negative pressure protection measures (generally air valves) in the pipeline are laid and the performance is reliable.

3. THEORETICAL ANALYSIS OF AIR VALVE LAYOUT

Air valves are commonly used for protection against water hammers; such protection effects are achieved owing to the rapid intake of air by air valves when the system is under a negative pressure, as well as the subsequent release of negative water hammer pressures, and these effects can be realized by reasonably setting the air valves in LGWSSs. In the presence of considerable amounts of gas, which complicate reductions in the drastic changes in system pressure caused by the gas, the air valve may undergo fatigue. When a pipe burst occurs, the pressure at the burst point rapidly decreases to the local atmospheric pressure, resulting in an instantaneous water hammer depressurization wave. The pressure drop wave propagates along the upstream and downstream directions of the pipeline. If the air valve is not appropriately arranged, the pipeline will be damaged. In the event of a water supply incident, direct harm and secondary hazards may have serious consequences. Although direct harm cannot be avoided when a burst occurs, secondary hazards must be avoided to prevent a series of pipe bursts. Therefore, it is important to determine a general criterion for the arrangement of air valves to prevent secondary pipe explosions. In secondary pipe explosions, concave-tube explosions are typically more dangerous. Concave-tube explosions involve a rapid release of energy, intense force propagation, and increased overpressure, thus leading to rapid propagation of the explosion to the secondary pipe. Conversely, convex-tube explosions are associated with gradual failure and slower release, thus allowing for some pressure dissipation and reduced force propagation to the secondary pipe. Accordingly, we investigated the influence of air valve arrangements on pipeline pressure under different concave pipeline laying methods in this study.

In this study, the local low point was selected as the dangerous tube burst point. The water pressure in the local low point is the largest, and it is easy to produce negative pressure at the high point of tube explosion here, which is the most unfavorable to the pipeline pressure after tube explosion.

In particular, the pipe section between two adjacent air valves was considered as the research object, and its length was approximately 500 m (the air valve arrangement spacing recommended by the American Water Works Association (2016) is 380–760 m). The pipe layout was simplified, and convex points with elevations higher than any air valve installation elevation and low points with elevations lower than any air valve installation elevation were retained. Therefore, any pipeline could be categorized into the following five types.

3.1. Surface pipeline bursting condition

As shown in Figure 2, the pipeline is an exposed penstock with a concave point. The top blue line represents the piezometric head. The black line represents the pipeline layout arrangement. The dangerous burst point is the local low point C of the pipeline between two adjacent air valves (A and B). Assuming that a burst occurs at point C, the head of the pressure-measuring pipe at point C will decrease to the elevation of the pipe centerline. Therefore, a pressure drop of ΔH will occur at the burst point, and the water hammer depressurization wave will propagate along the upstream and downstream directions of the pipeline.

Parallel lines l_1 and l_2 of the piezometric tube water level can be observed at burst point C. The elevation difference between the two parallel lines, ΔH_D, is the maximum vacuum control value of the water vaporization pressure.

In Figure 2, line l_1 intersects the pipeline laying arrangement line at points A and B. The water hammer depressurization wave generated at burst point C does not attenuate during propagation. In this case, the pressure-relief wave propagates

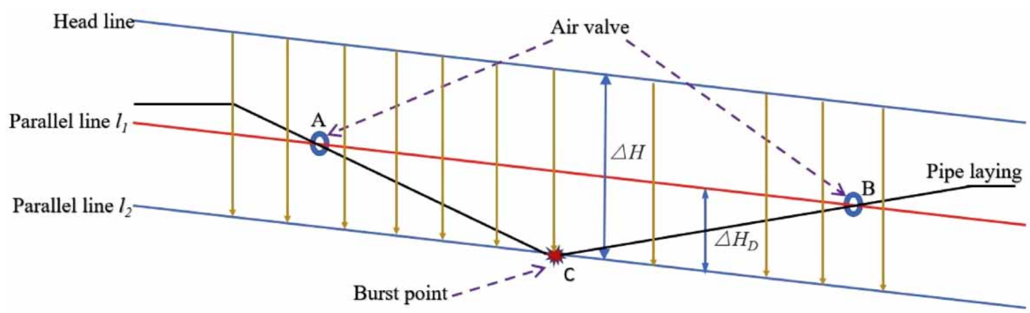


Figure 2 | Water hammer propagation schematic of ground pipeline after pipe burst. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

upstream from point A and downstream from point B, thereby further damaging the pipeline. Consequently, the vacuum degree of the water flow in the pipeline upstream of point A and downstream of point B exceeds the control value ΔH_D, resulting in damage to the pipeline. Therefore, facilities (air valves) near points A and B are required to balance the pressure and prevent or block continuous propagation of the ΔH pressure-relief wave.

We regard the head line and parallel line in the figure as horizontal lines. Because the model considers the pipe section between the two air valves as the research object, the spacing is small (always within 1,000 m), the resulting head loss along the way is minimal, and the local head loss caused by the bending of the pipe can be ignored; thus, the resulting hydraulic gradient is extremely small, approximately 1/1,000. Therefore, the head and parallel lines are regarded as horizontal lines. Moreover, it is justifiable to disregard the head loss as it poses no safety risks.

Therefore, under the condition of exposed penstock, the elevation difference between air valves A and B and the local low point C should be less than or equal to ΔH_D.

3.2. Buried pipe bursting conditions

The method depicted in Figure 3 represents a buried pipe laying with a concave point. The top blue line represents the piezometric tube water level. The black line represents the pipeline laying arrangement. The dangerous burst point is the local low point C of the pipe between two adjacent air valves (A and B). Assuming that a burst occurs at point C of the pipeline, the head of the pressure-measuring pipe at point C will theoretically decrease to h above the elevation of the pipe centerline (h is the actual pressure at the pipe burst point after the pipe burst occurs). The ΔH pressure drop at the pipe burst point is generated as shown in Figure 3, and a water hammer depressurization wave is formed and propagates along the upstream and downstream directions of the pipe.

The parallel lines l_1, l_2, and l_3 and the piezometric tube water level are directed upward along the burst pipe point C. The difference in elevation between lines l_1 and l_2 is ΔH_D. The elevation difference between the two parallel lines l_2 and l_3 is h.

In Figure 3, line l_1 intersects the pipeline laying arrangement line at upstream point A and downstream point B. Assuming that the water hammer pressurization wave generated at burst point C does not attenuate during the propagation process, the pressure drop wave will propagate upstream from point A and downstream from point B, thus further damaging the pipeline. Therefore, the vacuum degree of water flow in the pipeline upstream from point A and downstream from point B will exceed the control value ΔH_D, resulting in damage to the pipeline. Therefore, it is necessary to set up facilities (air valves) near points A and B to balance the pressure and prevent or block continuous propagation of the ΔH pressure drop wave.

Similarly, the parallel lines l_1, l_2, and l_3 and the piezometric tube water level can be regarded as approximately horizontal lines.

Therefore, under the condition of a buried pipe laying, the elevation difference between air valve A and local low point C should be less than or equal to the sum of ΔH_D and h.

3.3. Absent convex-and-concave-point pipe burst condition

Figure 4 presents a pipeline laid without convex and concave points. The top blue line represents the piezometric tube water level, and the black line represents the pipeline laying arrangement. The dangerous burst point lies at air valve A of the pipeline, which has a lower installation elevation. Assuming that a burst occurs at point A, the water head of the pressure-

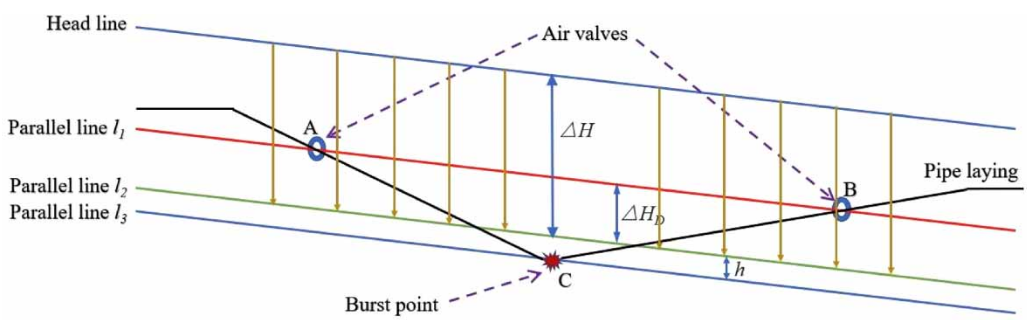


Figure 3 | Schematic diagram of water hammer propagation of the buried pipe after pipe burst. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

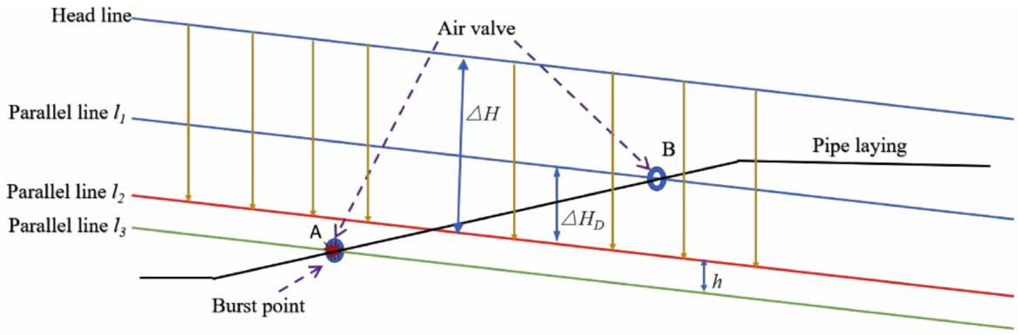


Figure 4 | Schematic diagram of water hammer propagation after pipe burst without convex and concave points between adjacent air valves. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

measuring pipe at point A quickly decreases to h above the elevation of the pipe centerline. As shown in Figure 4, the ΔH pressure decrease will occur at the burst point, and the water hammer pressurization wave will propagate along the upstream and downstream directions of the pipeline.

The parallel lines l_1, l_2, and l_3 and the piezometric tube water level are directed upward along burst point A, and the elevation difference between lines l_1 and l_2 is ΔH_D. The elevation difference between the two parallel lines l_2 and l_3 is h.

In Figure 4, line l_1 intersects the pipeline laying arrangement line at point B. Assuming that the water hammer pressure wave generated at pipe burst point A does not attenuate during the propagation process, the pressure wave propagates downstream of pipeline point B, thus further damaging the pipeline. The water flow vacuum downstream of point B exceeds the control value ΔH_D, resulting in damage to the pipeline. Therefore, it is necessary to set up facilities (air valves) near point B to balance the pressure and prevent or block continuous propagation of the ΔH pressure wave.

Similarly, lines l_1, l_2, and l_3 and the piezometric tube water level can be regarded as approximately horizontal lines.

Therefore, the installation elevation difference between air valves A and B must be less than or equal to the sum of ΔH_D and h.

3.4. Single convex-and-concave-point pipe burst condition

Figure 5 presents a pipeline layout with a concave point. Note that the exposed penstock with a concave point is not repeated here. A pipeline with a single convex point is shown in Figure 5. The top blue line represents the piezometric tube water level, and the black line represents the pipeline laying arrangement. The dangerous burst point is point B of the pipeline with a lower installation elevation. Assuming that a burst occurs at point B, the water level of the pressure-measuring pipe at point B decreases rapidly to h above the elevation of the pipe centerline. As shown in Figure 4, the ΔH pressure decrease will occur at the burst point, and the water hammer pressurization wave will propagate along the upstream and downstream directions of the pipeline.

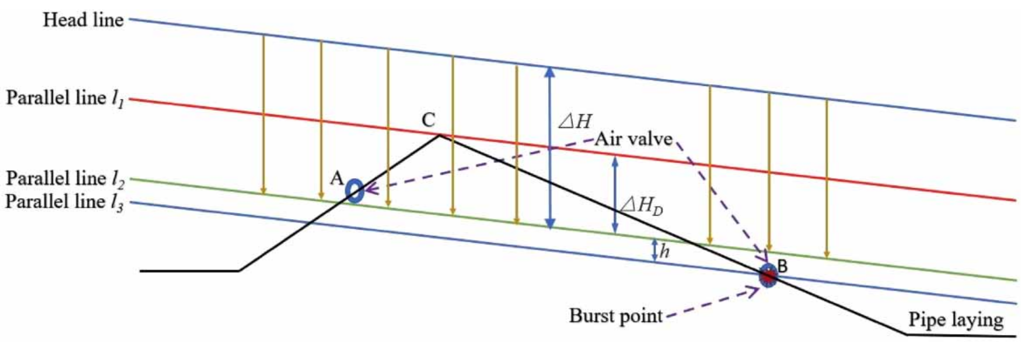


Figure 5 | Schematic diagram of water hammer propagation after convex-and-concave-point pipe burst between adjacent air valves. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

The parallel lines l_1, l_2, and l_3 and the piezometric tube water level are directed upward along burst pipe point B. The elevation difference between lines l_1 and l_2 is ΔH_D, and that between lines l_2 and l_3 is h.

In Figure 5, line l_1 intersects the pipeline laying arrangement line at points D and E. Assuming that the water hammer pressurization wave generated at burst point A does not attenuate during propagation, the pressure drop wave propagates upstream from point E and downstream from point D, thus damaging the pipeline. Consequently, the water flow vacuum in the pipeline downstream from point D and upstream from point E exceeds the control value ΔH_D, resulting in damage to the pipeline.

Similarly, lines l_1, l_2, and l_3 and the piezometric tube water level can be regarded as approximately horizontal lines.

Therefore, the installation elevation difference between convex-and-concave-point C and air valve B must be less than or equal to the sum of ΔH_D and h.

3.5. Double convex-and-concave-point tube-explosion condition

Figure 6 depicts the propagation of the water hammer after a pipe burst, wherein the pipeline is equipped with double convex-and-concave points located between adjacent air valves. As shown, the top blue line represents the water level in the piezometric tube, while the black line represents the arrangement of the pipeline. The critical burst point is denoted as the local low point D situated within the pipeline between two neighboring air valves, labeled A and B. Assuming that the burst occurs at point D, the water level in the pressure-measuring pipe at point B experiences a rapid height decrease denoted as 'h' above the pipe's centerline elevation. Consequently, a pressure drop ΔH occurs at the bursting point, as depicted in Figure 6. This pressure decrease triggers a propagation of water hammer pressure waves in both the upstream and downstream directions of the pipeline.

The parallel lines l_1, l_2, and l_3 and the piezometric tube water level are directed upward along the burst pipe point D. The elevation difference between lines l_1 and l_2 is ΔH_D, and that between lines l_2 and l_3 is h.

In Figure 6, line l_1 intersects the pipeline laying arrangement line at points E and F. Assuming that the water hammer pressure drop wave generated at burst point D does not attenuate during propagation, the pressure drop wave propagates upstream from point F and downstream from point E, thus further harming the pipeline. Therefore, the water flow vacuum in the pipeline downstream from point E and upstream from point F exceeds the control value ΔH_D, resulting in damage to the pipeline.

Similarly, l_1, l_2, and l_3 and the piezometric tube water level can be regarded as approximately horizontal lines.

Therefore, the elevation difference between the convex and concave points C and D must be less than or equal to the sum of ΔH_D and h.

3.6. Universal criteria

Figure 7 shows a pipeline diagram for preventing secondary pipe bursting at critical points. The blue line at the top represents the hydraulic head line of the pressure-measuring pipe, and the black line represents the layout and arrangement of the pipeline. The points at which there is pipe bursting danger are at the lowest point between two adjacent air valves (A and B). Points C and D respectively represent the highest and lowest points within the AB pipe segment (points C and D may overlap

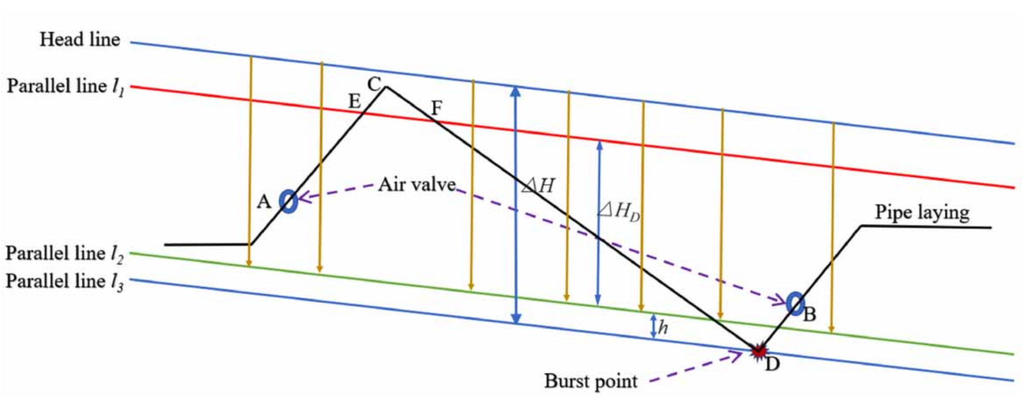


Figure 6 | Schematic of water hammer propagation after a pipe burst with double convex-and-concave-points between adjacent air valves. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

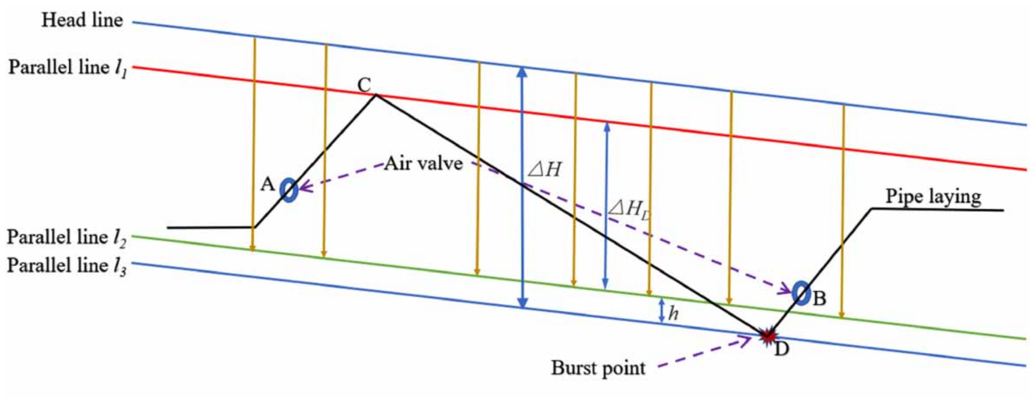


Figure 7 | Pipeline diagram for preventing secondary pipe bursting at critical points. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2023.089.

with points A and B). Assuming that D is the lowest point of the pipe segment, if a pipe burst occurs at point D, the hydraulic head of the pressure-measuring pipe at point B rapidly drops to an elevation h above the centerline of the pipe (where h represents the actual pressure at the burst point). Consequently, a pressure drop (ΔH) (see Figure 7) will occur at the burst point, forming a water hammer pressure reduction wave which propagates in the upstream and downstream directions along the pipeline.

Parallel lines l_1, l_2, and l_3 are drawn from the burst point D along the hydraulic head line. The elevation difference between l_1 and l_2 (ΔH_D) represents the maximum control value for the occurrence of vapor pressure in the flowing water. The elevation difference between l_2 and l_3 (h) represents the actual pressure at the burst point after the pipe burst. Assuming that the water hammer pressure reduction wave generated at point D does not attenuate during propagation, when this pressure wave reaches point C, it will no longer pose a threat to the pipeline, thus preventing further damage.

Similarly, l_1, l_2, and l_3 and the piezometric tube water level can be regarded as approximately horizontal lines.

Typically, distributed water hammer protection measures (air valves) are employed along a pipeline in LGWSSs. As long as the air valves are reasonably arranged, they can effectively block the propagation route of the ΔH depressurization wave through a large intake of air when a pipe burst occurs. The occurrence of a pipe burst is random, and the location of the burst point is difficult to determine. If the elevation of two adjacent air valves, pipeline convex point C, and concave point D are known, the elevation difference between the four points should, in theory, be approximately satisfied by Equation (9):

$$[|Z_A - Z_B|, |Z_A - Z_C|, |Z_A - Z_D|, |Z_B - Z_C|, |Z_B - Z_D|, |Z_C - Z_D|]_{\max} \leq \Delta H_D + h \quad (9)$$

where ΔH_D is the maximum vacuum control value of the pipe, and h is the actual pressure at the pipe bursting point after the pipe burst occurs, which is usually related to factors such as the pipe laying method and crater shape.

For convenient representation, set

$$\triangle Z_{\max} = [|Z_{\mathrm{A}} - Z_B|, |Z_A - Z_C|, |Z_A - Z_D|, |Z_{\mathrm{B}} - Z_{\mathrm{C}}|, |Z_{\mathrm{B}} - Z_D|, |Z_C - Z_D|]_{\max} \quad (10)$$

Thus, Equation (9) can be expressed as

$$\Delta Z_{\max} \leq \triangle H_D + h \quad (11)$$

The setting of the vacuum control value ΔH_D has a significant influence on pipeline safety after bursting. If this value is too small, more air valves will be required, increasing the project cost and affecting the overall strength of the pipeline. If the value is too large, secondary pipe bursts may be easily induced by the rapid propagation of depressurization waves because of the considerable distance between the flat pressure measures and pipe burst point. Under normal circumstances, the influence of the burst orifice size at the burst pipe on the pressure after pipe burst can be ignored in partial safety meters. The maximum vacuum control value ΔH_D is typically 8 m. For an open pipe laying, $h = 0$, whereas for buried pipes, h is the thickness of the soil covering the upper part of the pipeline.

4. CASE STUDY

4.1. Basic information

A long-distance gravitational water supply project was considered; this project featured a double-pipe water supply, a total water transmission line length of approximately 38.2 km, a pipe diameter of 2.4 m, buried pipe laying, an overburden of 3 m, ductile iron pipe material, and a water hammer wave velocity of approximately 1,000 m/s. The design flow was 15 m^3/s, the water level of the inlet pool was 65 m, and the design elevation of the pipe center at the starting point of the pipeline was 61.5 m.

To ensure the stable and safe operation of a water conveyance system, each pipe section of an LGWSS should ensure that the maximum pressure of each pipe section does not exceed the standard pipeline pressure, and it must prevent the occurrence of a negative pressure along the pipeline or a negative pressure less than the control standard after a pipe burst. Under these control standards, a numerical simulation analysis of the project was performed using the characteristic line method. Considering certain pipe sections as examples, the air valve layout is shown in Figure 8.

The air valves of the pipe section were numbered, and the elevation difference between adjacent air valves and the middle convex and concave points was calculated. The air valve setting parameters are listed in Table 1.

4.2. Air valve protection under pipe bursting condition

In practical engineering, the pipe burst point exhibits a certain randomness. Generally, points such as local high points of the pipeline, pipe turning points, and pipe joints are prone to pipe bursting. However, we mainly investigated whether secondary pipe bursts could be prevented under the most unfavorable pressure conditions for a pipe burst in this study; therefore, the local low point with the maximum internal water pressure was selected as the dangerous tube burst point in this study. After bursting, the pipeline pressure decreased sharply. Air valves can effectively block the water hammer pressure wave propagation path, which is generated at the burst point, to ensure that the system does not cause secondary incidents in a short time.

For the water supply system, we mainly analyzed whether the layout of the air valves could prevent a secondary burst in this study. The pipe section between Av6 and Av7 had a concave point with a pile number of K3 + 164.474 and a pipe center elevation of 43.15 m. It had an elevation difference of 11.6 m from Av6 that exceeded the standard in Equation (11) by 11 m. Therefore, the pipe burst at the low point of this section was calculated. To verify the rationality of Equation (11), an air valve (installation elevation of 48.655 m) was added at pile number K2 + 739.925 for comparative pipe burst evaluations. The pipe section between Av8 and Av9 had no convex or concave points; however, the installation elevation difference of the air valves was 16.976 m, exceeding the standard 11 m of Equation (11). Therefore, the local low point

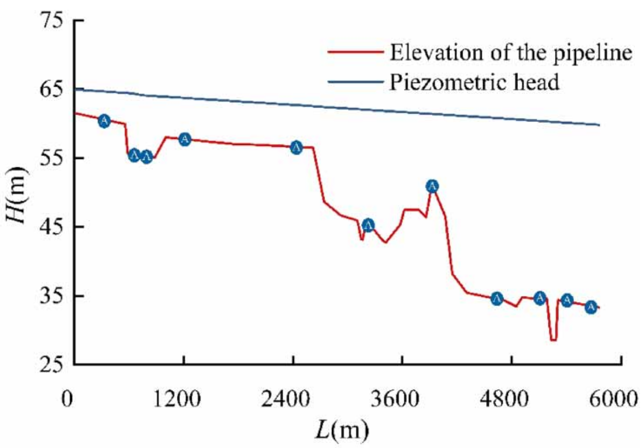


Figure 8 | Air valve layout along the line.

Table 1 | Air valve setting parameters

	Distance	Elevation	ΔZ_{max}	Remark
Av1	254.583	60.801		
Av1–Av2	/	/	5.201	Single convex and concave points
Av2	602.98	55.6		
Av2–Av3	/	/	0.525	Without convex and concave points
Av3	742.287	55.075		
Av3–Av4	1,001.934	58	2.925	Single convex and concave points
Av4	1,273.181	57.643		
Av4–Av5	/	/	0.696	Without convex and concave points
Av5	1,919.802	56.947		
Av5–Av6	/	/	0.38	Without convex and concave points
Av6	2,519.802	56.567		
Av6–Av7	3,164.474	43.15	13.417	Single convex and concave points
Av7	3,221.474	45.169		
Av7–Av8	3,419.474	42.753	7.74	Single convex and concave points
Av8	3,914.516	51.152		
Av8–Av9	/	/	16.976	Without convex and concave points
Av9	4,739.368	34.176		
Av9–Av10	4,849.79	33.458	1.145	Single convex and concave points
Av10	5,176.222	34.603		
Av10–Av11	5,284.474	28.55	6.053	Single convex and concave points
Av11	5,760.545	33.321		

near the section was selected to obtain the pipe burst conditions. To verify the rationality of Equation (11), an air valve (the installation elevation is 42 m) was added at pile number K4 + 068.715 for comparative analysis of the pipe burst. The valve layout diagrams near dangerous points 1 and 2 are shown in Figures 9 and 10, respectively.

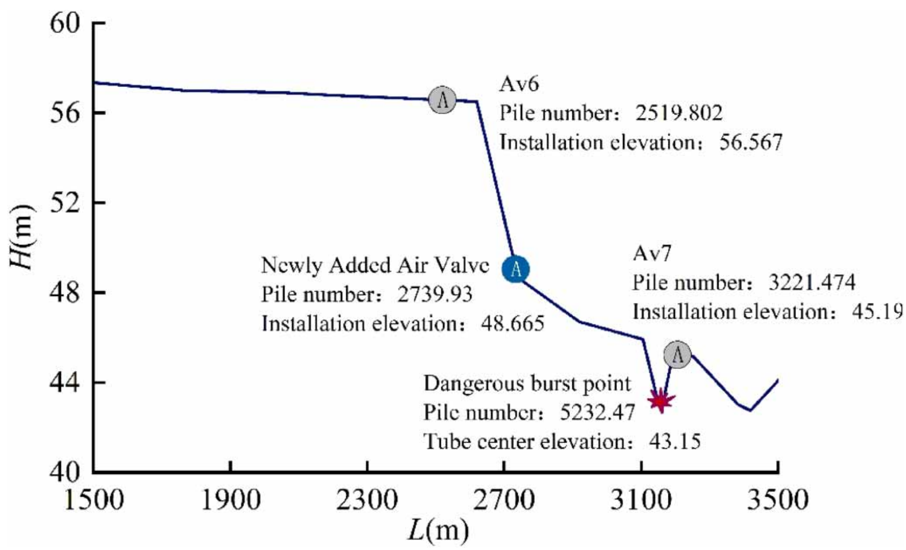


Figure 9 | Air valve layout diagram of dangerous burst point 1.

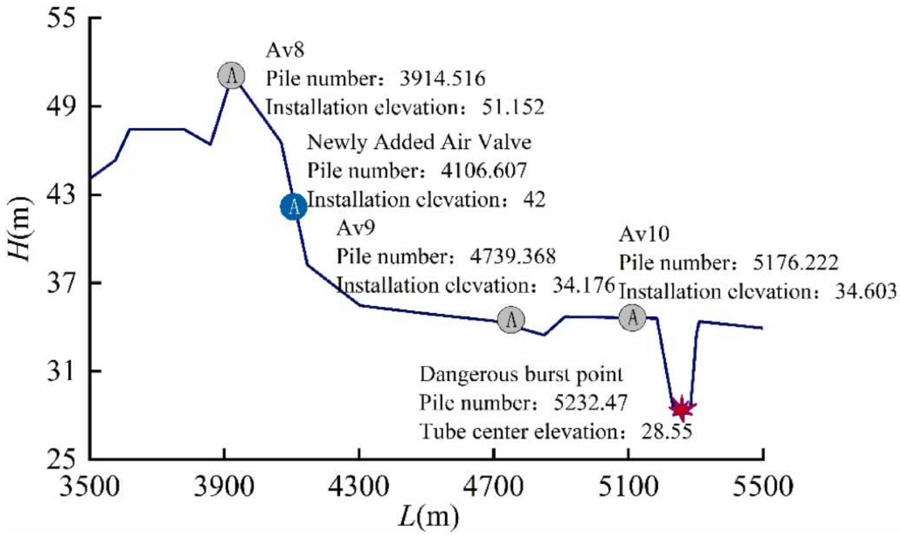


Figure 10 | Air valve layout diagram of dangerous burst point 2.

4.3. Results and discussion

The hydraulic transient process of the example project was analyzed by applying the hydraulic model to the burst pipe. The burst pipe occurred within 0.2 s, and the upstream and downstream valves of the burst point remained open. The pressure and flow changed at the same burst point before and after the addition of the air valve, the maximum and minimum pressure enveloped upstream and downstream of the burst point, respectively, and the air intake of the new air valve could be obtained, as shown in Figures 11 and 12.

As shown in Figures 11 and 12, the pressure at the bursting point changed significantly. In a short period, the pressure at the bursting point decreased from the initial pressure to 3 m (covered by approximately 3 m of soil). Subsequently, owing to the local resistance of the bursting pipe orifice, the pressure increased slightly and stabilized at a lower pressure level. The corresponding pressures of the two burst conditions stabilized at 7.7 and 21.2 m, respectively. The leakage flow at the bursting point increased rapidly from the initial flow rate of 7.5 m^3/s and then stabilized at a higher flow rate. The corresponding flow rates of the two burst conditions stabilized at 14.7 and 18.4 m^3/s, respectively. The added air valves both experience a small amount of air intake after burst. Before and after the addition of the air valve, minor changes occur in the maximum pressure of the pipeline, but the minimum pressure of the pipeline (especially at locations near the extreme point) increases (after the addition of the air valve). The pressure statistics for the two dangerous burst points are summarized in Table 2.

The listings in Table 2 show that before adding air valves, the pressure in some pipe sections is lower than the minimum pressure control standard. Before adding the air valve, the pipe bursts at the dangerous pipe burst point 1, and the negative pressure of −9.4 m is generated near K2 + 619.925, which is smaller than the minimum pressure control standard when the pipe burst (−8 m); it is thus easy to cause a secondary pipe burst. Before adding the air valve, the pipe burst occurred at the second dangerous pipe burst point, and the negative pressure of −10.84 m was generated near K4 + 068.715; this pressure was less than the minimum pressure control standard after the pipe burst, and is thus easy to cause the second pipe burst. After the addition of the air valve and tube explosion, although serious water hammer depressurization is generated in the system, the minimum negative pressure at the first point at which there is a tube-explosion danger was higher than −7.73 m owing to the reasonable arrangement of the air valve, and the minimum negative pressure at the second danger point of pipe explosion was controlled higher than −4.88 m; both of these values are within the minimum pressure control standard range after pipe explosion, and can effectively cut off the water hammer wave propagation route.

5. CONCLUSIONS

This study has made significant contributions to the field of LGWSSs by addressing the propagation of water hammer waves triggered by primary pipe bursts and by preventing secondary pipe bursts. The findings and results of this research study have scientific and practical value. Scientifically, the study established a mathematical analysis model to allow the understanding

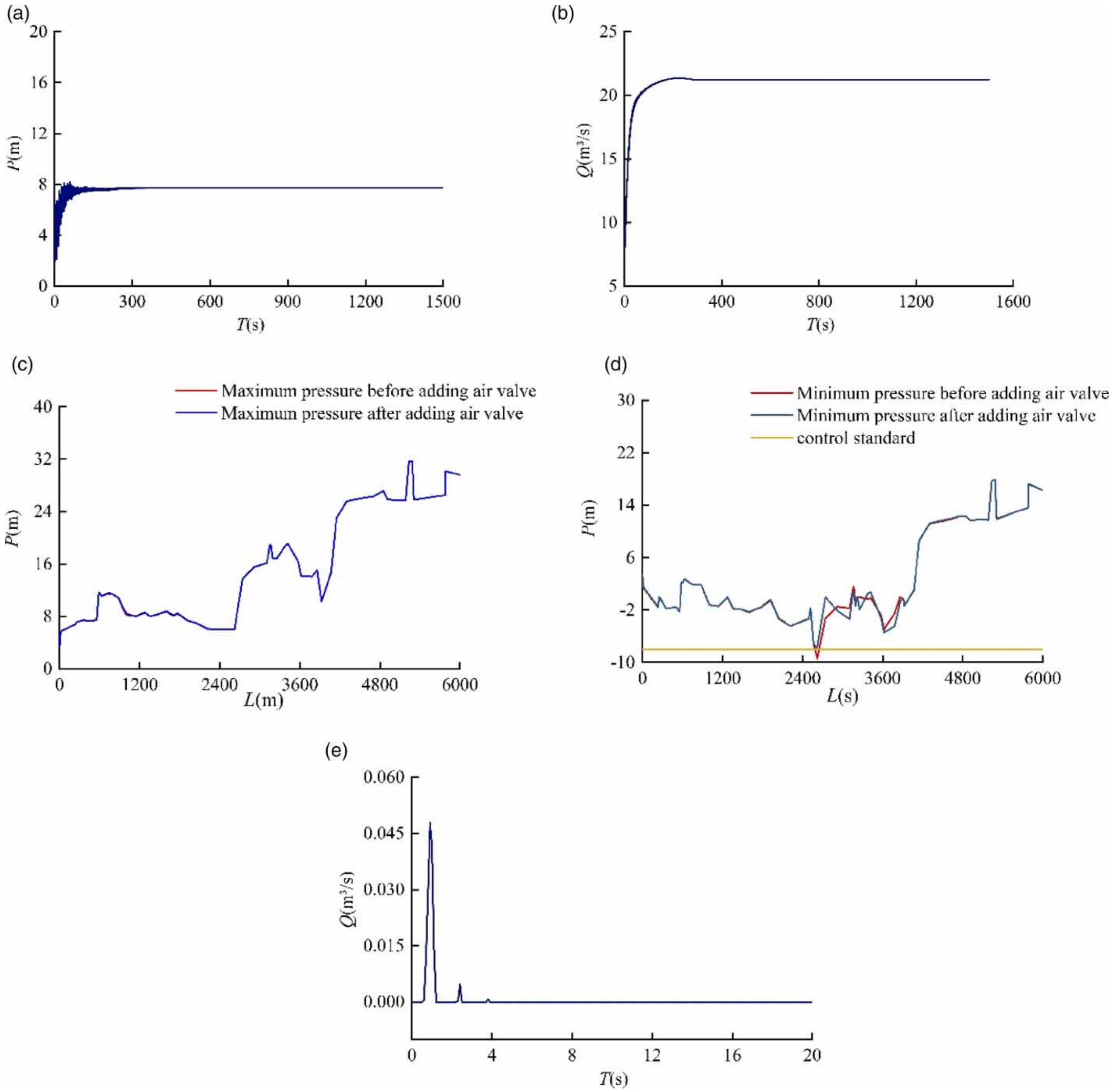


Figure 11 | Variation of hydraulic parameters of pipe burst at dangerous point 1 without valve closing. (a) Pressure of burst point. (b) Leakage of burst point. (c) Maximum pressure envelope of pipeline. (d) Minimum pressure envelope of pipeline. (e) Inlet air volume of new air valve.

of pipe bursts in buried pipes, thus providing a foundation for further research in this area. Additionally, the proposed air valve arrangement criteria contribute to scientific knowledge regarding the effective placement of air valves in LGWSS pipelines, based on a comprehensive understanding of the physical process of pipe bursts. In terms of applicability, the developed air valve arrangement criteria have important engineering applications. Implementing these criteria ensures reasonable and effective placements of air valves, thereby mitigating the risk of secondary pipe bursts in LGWSSs. The detailed installation proposal for the elevation of air valves aids the practical implementation of these criteria, thus enhancing the reliability and efficiency of water supply systems. However, it is important to acknowledge the limitations of this study. The research focused on addressing water hammer waves triggered by primary pipe bursts; however, there may be other factors or phenomena contributing to pipe bursts in LGWSSs that were not considered. Future studies should aim to address these limitations and explore additional factors, such as pipe materials, soil conditions, and operational factors. This study contributes to the

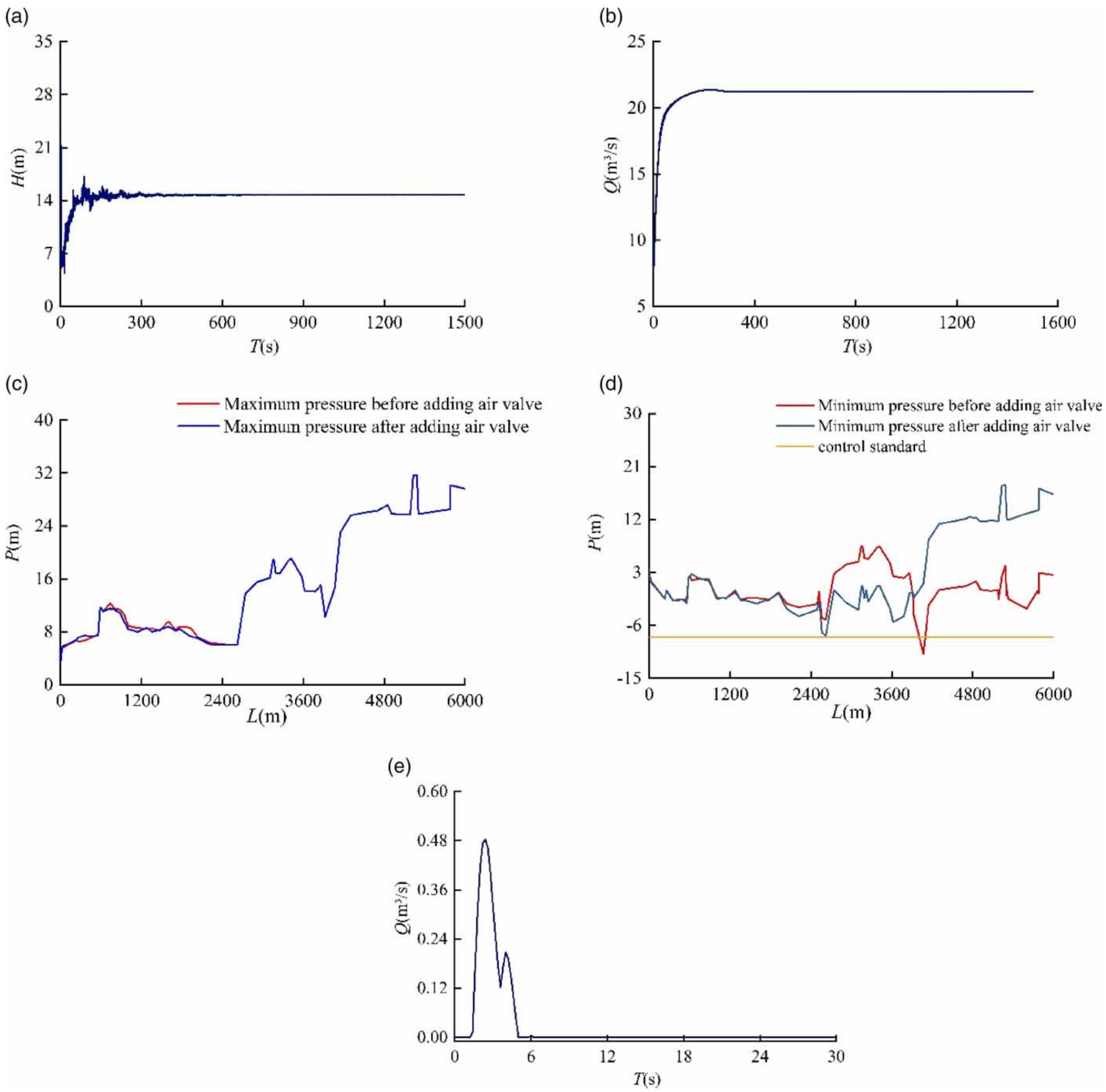


Figure 12 | Variation of hydraulic parameters of pipe burst at dangerous point 2 without valve closing. (a) Pressure of burst point. (b) Leakage of burst point. (c) Maximum pressure envelope of pipeline. (d) Minimum pressure envelope of pipeline. (e) Inlet air volume of new air valve.

Table 2 | Calculation results of pipe burst at different positions without valve closing

Position of pipe break	Minimum pressure before adding air valve	Minimum water hammer pressure pile number	Minimum pressure after adding air valve	Minimum water hammer pressure pile number	Minimum pressure control standard
Dangerous burst point 1	–9.4	K2 + 619.925	−7.73	K2 + 619.925	–8
Dangerous burst point 2	–10.84	K4 + 068.715	−4.88	K2 + 619.925	–8

scientific understanding and practical applications of preventing secondary pipe bursts in LGWSSs. The mathematical analysis model, air valve arrangement criteria, and installation proposal provide valuable insights and guidance for engineers and water supply authorities. Additional research and exploration of additional factors will improve the reliability and efficiency of LGWSSs, thus ensuring a more resilient water supply infrastructure for communities.

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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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