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Transient hydraulic analysis of the water delivery pipeline in mountainous areas for cascade pressurized pump stations

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ABSTRACT

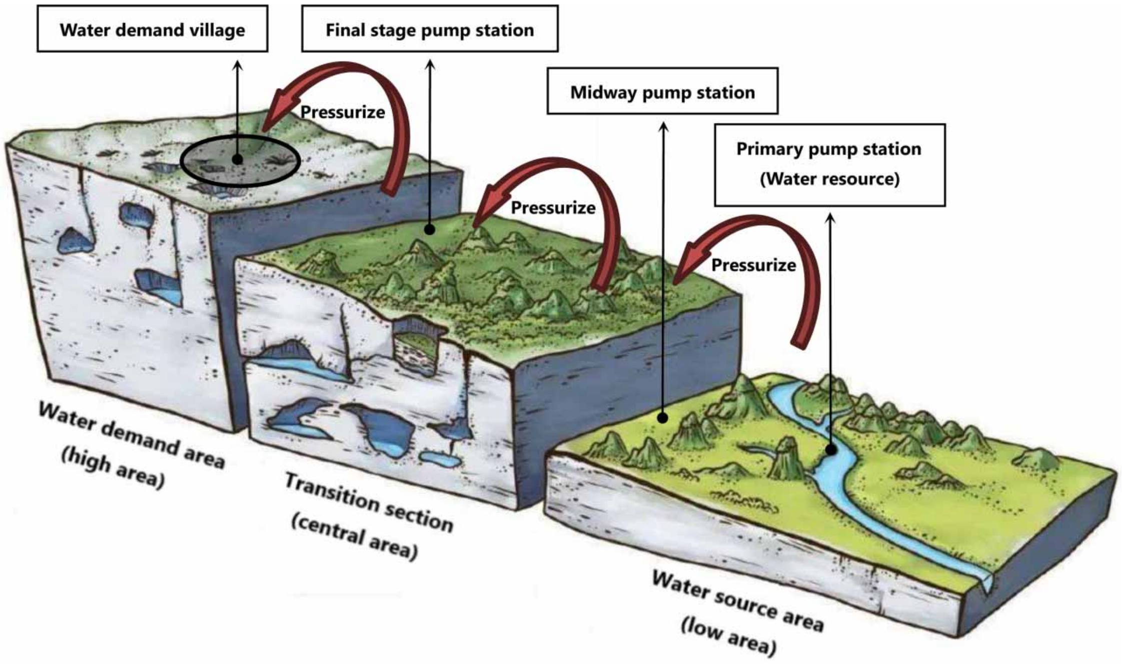
Aiming at the problem that cascade pressurized pump stations in mountainous areas are more prone to pump shutdown accidents compared to single-stage pressurized pump stations. Various pump shutdown accidents that may occur in the pressurized water supply system of the cascade pumping station were analyzed in a targeted manner. Additionally, it was also explored that in addition to water hammer protection measures, remote-control measures for water pumps based on PLC (Programmable Logic Controller) may be used to reduce the severity of accidents. A single-factor experimental method was used to numerically analyze various accident conditions of a simplified model of a three-stage series pressurized water delivery system consisting of a water intake pump station, a midway pump station, and a final-stage pump station, without water hammer protection devices. The impact of different control variables on the transient hydraulic calculations of pumping stations at all levels was evaluated. The results showed that optimizing the precedence of shutdowns, and the sequential shutdown times of each stage pump station could be assisted to some extent in water hammer protection by the PLC. This provides technical support and detailed optimization for the scientific control of cascade booster pumping stations in mountainous areas.

Key words: cascade pump stations, numerical simulation, pump shutdown accidents, transient hydraulics

HIGHLIGHTS

- The effect of pump shutdown time difference on accidents is optimized with a frequency of 1 s.
- Theoretically, the accident number of pump stations is directly proportional to water hammer damage.
- Regulating the pump shutdown precedence cannot solve the pressurization problem caused by the midway pump shutdown accident.
- Shutdown the pump stations sequentially in line with the flow direction can lead to more severe water hammer incidents.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The proportion of mountainous areas in China is relatively large, but the distribution of freshwater resources related to them is scarce, resulting in a prominent contradiction between water supply and demand (Liang 1988). However, compared to plain areas, mountainous areas are more prone to water hammer accidents due to their complex geographical characteristics, resulting in huge property losses and adverse social impacts (Wang *et al.* 2012). As an essential part of the long-distance water transportation system in mountainous areas, the high speed and stable operation of pump stations is a prerequisite for ensuring safe water transportation. To minimize the overall energy consumption of the water transmission system and reduce the operating costs when transporting water to remote mountainous areas, it is often considered to set up midway pump stations at intervals along the water transmission pipeline. The pump stations operated in this way can also be referred to as cascade pump stations. Compared with single-stage pumping stations for pressurized water transportation, multi-stage series pressurized pumping stations have the advantages of low investment and low energy consumption, and have been widely used in long-distance oil pipelines (Bao *et al.* 1996). However, there are more complex scheduling and management issues during shutdown maintenance and water balance at cascade pump stations, such as the need to set operating procedures such as the total number of pump shutdowns, the precedence of pump shutdown, and the differences of pump shutdown time. Compared to a single-stage pump station, it is more likely to cause pump shutdown accidents and cause severe damage to the water delivery system.

So far, there are few research results on the simulation of pump shutdown accidents in cascade pumping stations. Conversely, most of the research focuses on numerical simulation analysis of parallel pressurized pumping stations (Feng & Qiu 2013; Olszewski 2016; Feng *et al.* 2020). Some scholars mainly focus their research on the optimization and analysis of water hammer protective equipment, with emphasis on the selection and application of water hammer protective equipment (Feng *et al.* 2008). In addition, some typical studies combine computer technology with mathematical formulas to evaluate whether the calculation accuracy of the former meets practical application needs (Lu *et al.* 2018). It is obvious that previous experts and scholars have not established the reasons and influencing factors that cause pump shutdown accidents in cascade pumping stations as their primary research objectives. Therefore, further analysis and verification are needed for the water hammer accident caused by cascade pump stations in mountainous areas, and the potential influencing factors leading to the water hammer accident still need to be further explored and studied.

This paper focuses on the remote-control system for water pumps in cascade pressurized pump stations, simulating the settings of the number, precedence, and time of pump shutdown in its backend program. The impact of the above operations was explored on various possible pump shutdown water hammer accidents. Specifically, a single-factor optimization method was used for experimental design. The averaging method was used as the sampling method. Modeling and calculation were carried out using Bentley Hammer software to simulate various possibilities of pump shutdown accidents caused by cascade pressurized pump stations. The influence of pump shutdown precedence and time difference on transient calculation results was also explored. It is worth mentioning that this work can visualize which pumping outages can be mitigated by the pumping outage time difference and provide a theoretical and guiding basis for practical engineering.

2. THEORETICAL REVIEW OF WATER HAMMER

2.1. The concept and causes of water hammer

A water hammer is known as a hydraulic transition process. It is a form of motion of a fluid in a non-stationary state (Wylie & Streeter 1993). Specifically, it refers to the state in which the flow velocity, acceleration, dynamic pressure, shear stress, and density of the fluid at all spatial points change with time and space (Ghidaoui *et al.* 2005).

In practical engineering, the flow velocity in pressurized pipelines often undergoes drastic changes, leading to momentum conversion and a series of sharp fluid impact phenomena in the pipeline, which is known as the water hammer phenomenon (Chaudhry 1987). In the phenomenon of water hammer, the main role is played by the inertia and compressibility of the fluid itself (Guo *et al.* 2014). The former is required to maintain the original motion state of the fluid, while the latter promotes a change in the motion state of the fluid. The contradictory relationship between the above two factors is the essence of the water hammer phenomenon.

Water hammer can prompt numerous hazards such as pressure waves, pipe rupture, cavitation, and corrosion, breaking the pipes; consequently, it is vital to analyze this phenomenon during both the design and operation phases (Allievi 1925).

According to the differences in pump shutdown time, the water hammer can be divided into direct water hammer and indirect water hammer. Among them, the water hammer duration refers to the total time required for the propagation and reflection of water hammer waves in the pipeline. Equation (1) is known as the basic equation of a pressure wave period (Ramos & Almeida 2001).

$$t_w = \frac{2L}{c} \tag{1}$$

where t_w is the pressure wave period, L denotes the total length of the water transmission pipeline, c and represents the velocity of water hammer waves.

When the duration of the pump shutdown is less than the water hammer phase, the reflected wave of water hammer pressure cannot return to the water pump in time. The pressure increase at the water pump is only associated with the direct wave and not with the reflected wave. This phenomenon is called a direct water hammer. Conversely, if the pump stops for a longer time than the water hammer phase, the pressure rise value at the pump is partially offset by the reflected pressure drop wave, and this phenomenon is called an indirect water hammer. Obviously, the impact force of a direct water hammer on water transmission pipelines is greater than that of an indirect water hammer, but in practical engineering, an indirect water hammer is more common (Streeter & Lai 1962).

2.2. Full characteristic curve of water pump

During the operation of a water pump, its characteristics are also constantly changing. For example, the speed, head, flow rate, and torque of the water pump may change at any time under different working conditions. These motion parameters can be positive or negative. In the face of so many variables, it is increasingly crucial and indispensable to systematically, quantitatively, and comprehensively examine the operating conditions of water pumps, and thus the full characteristic curve of water pumps should emerge accordingly.

The similarity theory of water pumps is the theoretical basis for improving the full characteristic curve of water pumps (Li *et al.* 2014). Equation (2) can be used to represent the parameters for similar operating conditions of the same water pump.

$$\begin{cases} \beta = \dfrac{N}{N_n} \\ h = \dfrac{H}{H_n} \\ \nu = \dfrac{Q}{Q_n} \\ m = \dfrac{M}{M_n} \end{cases} \tag{2}$$

where N is the rated speed of water pump, H the rated head of water pump, Q the rated flow rate of water pump, M the rated torque of water pump, N_n is the actual speed of water pump, H_n the actual head of water pump, Q_n the actual flow rate of water pump, and M_n the actual torque of water pump.

The full characteristic curve of the water pump is essentially based on ν Is the horizontal axis, β the equal h or equal m curve of the vertical axis. However, a water pump only corresponds to a few characteristic points, and a large number of experiments are required to fully draw the full characteristic curve of the outlet pump (Suter 1966). In view of this, the expression form of the full characteristic curve of the water pump can be transformed as shown in Equation (3).

$$\begin{cases} x = \pi + \tan^{-1}\left(\dfrac{\nu}{\beta}\right) \\ WH(x) = \dfrac{h}{\beta^2 + \nu^2} \\ WM(x) = \dfrac{m}{\beta^2 + \nu^2} \end{cases} \tag{3}$$

The transformed full characteristic curve of the water pump takes x as the abscissa, and $WH(x)$ and $WM(x)$ as the ordinates. The amplitude of the change in the abscissa is $x \in [0, 2\pi]$. If 88 small intervals are divided in four steps of $\Delta x = 0.071$ within this interval, a total of 89 discrete points where x intersects with $WH(x)$ and x intersects with $WM(x)$ can be obtained (Knapp *et al.* 1970). Therefore, with the intervention of the linear interpolation method, the above transformation can basically make the full characteristic curve of the water pump continuously drawn and calculated more persuasively within the corresponding range.

2.3. Accident operation status of water pumps

When a pump shutdown accident caused by abnormal operation suddenly occurs in a long-distance water transmission pipeline in mountainous areas, the form of fluid in the pipeline undergoes significant changes (Filion & Karney 2002). Especially for pump units that have not adopted any water hammer protection measures, their working conditions can be roughly divided into the following conditions (Zou *et al.* 2016).

- The condition of power outage: Due to the sudden loss of power source of the water pump unit during pump shutdown, the impeller of the water pump only maintains its original state of rotation due to inertia, but the speed will decrease.
- The condition of braking: In the downstream pressure flow pipeline of the water pump unit, the fluid flowing toward the high-level water tank is first gradually reduced to zero under the influence of instantaneous inertia, and then accelerated to flow back to the water pump unit under the action of gravity head.
- The condition of the turbine operating: As the flow rate of the fluid flowing back to the water pump unit continues to increase, the impact force formed by the backflow fluid on the water pump impeller gradually becomes stronger, causing the original rotation direction of the water pump impeller to gradually decrease to zero, then rotate in the opposite direction and gradually accelerate until the runaway speed.

Based on the above phenomena, it can be explained that the check valve is one of the safety devices in water pumps. Even if the valves do not provide necessary protection for the water transmission pipeline under transient conditions, they can be canceled in low-head water transmission systems with water hammer protection devices. It can still provide necessary protection for the pump group (rotor and motor) in most pump shutdown accident conditions of cascade pressurized pumping stations, to prevent damage to the pump impeller due to long-term reverse rotation (Thorley 1989; Gülich 2014).

None of the above operating conditions belong to the normal operating conditions of the water pump, they are nevertheless included in the research scope of the full characteristic curve of the water pump (Hasmatuchi *et al.* 2009).

3. MODEL CREATION AND RESEARCH METHODS

3.1. Definition and creation of calculation models

The modeling was simplified based on actual long-distance mountain engineering (Qingdao Beizhai Water Diversion Project, Shandong Province, PR China) as shown in Supplementary material, Fig. S1 and Fig. S2. The calculation model was constructed using Bentley Hammer v10.08 software (Haimes & Hall 2010), consisting of a water intake point, a primary pressurized water pump, a midway pressurized water pump, a final-stage pressurized water pump, and a water consumption point (Liu 2020). The local resistance coefficients are set based on data referenced to 'Standard for the design of outdoor water supply engineering' and 'Standard for pumping station design' and to the equipment manufacturer, which matched to the local loss database within the software. According to the international standard ISO 2531-2009, ductile iron water pipes of DN300K9 grade, 7.2 mm wall thickness, and 49-bar maximum working pressure are connected to each other. The total length of the water transmission pipeline is 10 km, with a maximum elevation difference of 290 m. Nodes are set up at appropriate locations along the pipeline. The pipes are connected by overall expansion, with a wave speed of 1035.17 m/s and a time calculation step of 0.1 step distance, resulting in a total simulation time of 300 s.

The selection of pressurized water pump units at all levels is completely consistent. Based on design selection and market research, the main rated technical parameters of the water pump have been determined to be 360 m^3/h flow rate, 100 m head, 80% efficiency, and 2,475 r/min rotational speed.

Supplementary material, Fig. S3 shows the characteristic curve drawn using the definition types of 'one design point' and 'highest point efficiency' in software. It can ensure that the water pump meets the requirements of the design flow rate and design head when operating within the high-efficiency range.

3.2. Definition and creation of calculation models

The single-factor optimization method is a relatively traditional approach for experimental analysis. Specifically, there is only one influencing factor, or although there are multiple non-interacting influencing factors, when arranging the experiment, only one of the factors that affect the indicator is considered as the control variable, and the other factors are used as the control quantification to maintain the same experimental design method as much as possible (Linaweaver & Clark 1964). To ensure the reliability and rationality of the obtained experimental results, a uniform distribution method is used for screening. Specifically, according to the accuracy requirements and actual situation, experimental points are evenly arranged, and experiments are conducted on each experimental point and compared with each other to obtain the best advantage.

Figure 1 shows how to use the single-factor optimization method for research through a flowchart, and it is divided into five steps in total. The first step is to determine the research objective, which is clearly stated in the abstract. The second step is to examine the influencing factors. After combining previous papers with actual engineering, the influencing factors will be determined as the total number of shutdowns, the precedence of the shutdown, and the shutdown time of each stage pump station. The third step is to analyze the internal relations, based on the actual controllability of influencing factors, analyze from simple to complex in order of the total number of shutdowns, the precedence of shutdown, and the shutdown time of each stage pump station. The fourth step is to successive optimization, and the fifth step is to identify the main influencing factors.

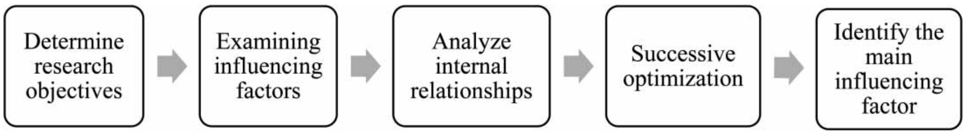


Figure 1 | The steps of a single-factor optimization method.

In view of this, adopting this method must first assume that there is no interaction between the various factors. Based on the consideration of the independent roles played by the total number of pump shutdowns, the precedence of pump shutdown, and the shutdown time of the pump in affecting pump shutdown accidents in cascade pressurized pump stations, it is confirmed that the single-factor optimization method can be used.

4. TRANSIENT HYDRAULIC ANALYSIS

4.1. The impact of total pump shutdown number

To investigate the impact of the total pump shutdown number on the transient calculation results, the combination of pump shutdown in the calculation model is used as the control variable, and the pump shutdown time is considered as the control quantity. Assuming that the water pump shutdown simultaneously at a certain moment, after probability event statistical analysis, there are a total of eight types of pump shutdown combinations (combination number: X1–X8), with a minimum number of 0 and a maximum number of 3. All combinations are calculated by substituting them into the hammer software, and the results of all calculations are organized and summarized in Table 1.

Table 1 | Transient hydraulic calculation results of combination X1–X8

Combination	Primary pump	Midway pump	Final stage pump	Shutdown number	Max. head (m)
X1	√	√	√	0	305.88
X2	×	√	√	1	305.88
X3	√	×	√	1	331.02
X4	√	√	×	1	343.39
X5	√	×	×	2	386.79
X6	×	√	×	2	350.44
X7	×	×	√	2	397.01
X8	×	×	×	3	411.34

It was found that when the primary pump station, midway pump station, and final-stage pump station shutdown simultaneously, the maximum pressure head that appears in the water transmission pipeline is 411.34 m. When all pump stations are operating normally, the maximum pressure head that occurs in the water delivery pipeline is 305.88 m, which means that the calculation of combination X8 is 1.345 times that of combination X1. In addition, by comparing the maximum pressure head calculated by combinations X1–X8 horizontally, it can be seen more intuitively that the number of pump shutdown is positively correlated with the calculated value of the maximum pressure head.

To further verify and evaluate the pressure situation of the water transmission pipeline, the combined X1 and X8 were used as an example for comprehensive analysis. The hydraulic envelope curve of combination X1 is shown in Figure 2. The horizontal axis represents the distance between the primary pump and the water consumption point, and the vertical axis represents the elevation. The green curve below represents the laying elevation of the center of the cross-section of the water transmission pipeline, and the red curve above represents the hydraulic slope line under normal operating conditions. Under normal operating conditions, the water pump unit operates at high speed under a constant head, and its rated flow rate is completely consistent with the actual water delivery volume of the water delivery system, and both are constant values. Under the influence of the frictional resistance and local resistance of the pipeline system, the hydraulic gradient line gradually decreases. Due to the absence of a water hammer, all pipelines were operated under normal pressure, confirming that they would not be damaged.

Figure 3 shows the hydraulic envelope curve of the X8 combination. The green curve below represents the laying elevation of the center of the cross-section of the water transmission pipeline, and the red curve and blue curve respectively indicate the maximum and minimum pressure heads that occur in the water transmission pipeline under the action of the water hammer. Obviously, some of the pipelines have developed a negative pressure state under the action of the water hammer.

By comparing Figure 3 with Figure 2, it is known that the maximum pressure head values of the water transmission pipeline in combinations X1 and X8 occur in the downstream section of the final-stage pump station. In particular, the combination X8 was in a temporary negative pressure operation state in some water transmission

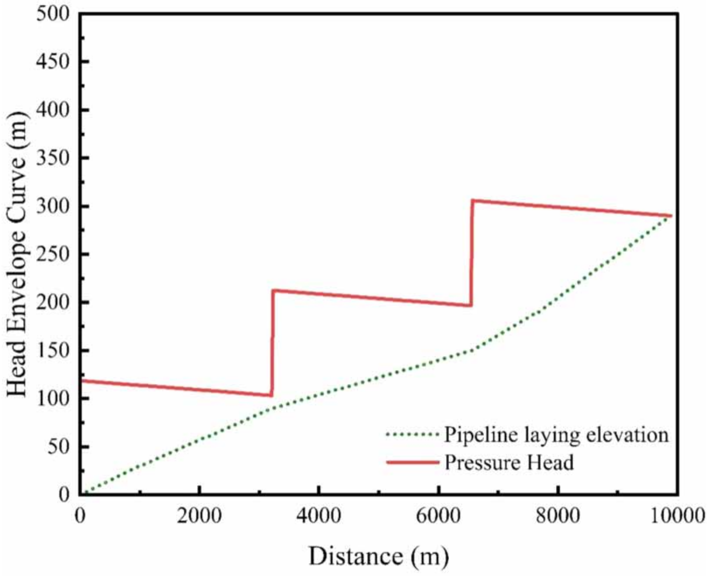


Figure 2 | Hydraulic envelope curve of sequence combination X1.

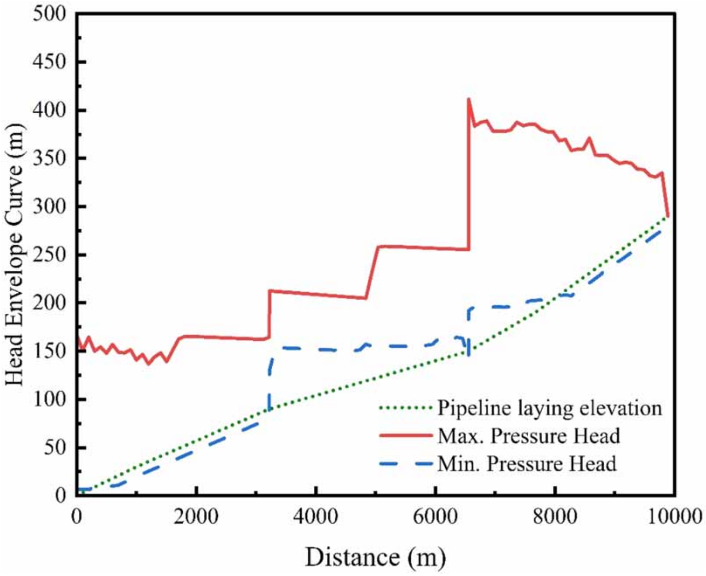


Figure 3 | Hydraulic envelope curve of sequence combination X8.

pipeline sections under the influence of a water hammer, which resulted in a sudden increase in the pressure head at the outlet of the final-stage pump station in a short period of time. Although it did not exceed maximum working pressure, it still needs to be given sufficient attention. The final-stage pump station, with its related components, is a key object for considering the protection water hammer.

4.2. The impact of pump shutdown precedence

In practical engineering, in order to ensure the safe and stable operation of the water transmission system, the mountainous long-distance water transmission system using cascade pump stations needs to balance and control the water transmission throughout the entire line (Liu *et al.* 1995). According to the water hammer experiment conducted by the Dutch Delta Institute, the second peak water hammer pressure measured at the fifth second is the highest among all water hammer pressure peaks in the transmission process of water hammer waves (Bergant *et al.* 2013). Therefore, to evaluate the impact of pump shutdown precedence at all levels of pump stations on the results of transient calculation, the pump shutdown time difference was taken as a controlled quantity and considered uniformly over a 5-s interval. In this way, six combinations of pump stations at different levels are formed in different pump shutdown precedence, and each combination is calculated using software. The results of all calculations are organized and summarized as shown in Table 2.

Table 2 | Transient hydraulic calculation results of combination Y1–Y6

Combination	Primary pump shutdown precedence	Midway pump shutdown precedence	Final stage pump shutdown precedence	Max. head (m)
Y1	First	Second	Third	496.77
Y2	First	Third	Second	331.02
Y3	Second	First	Third	455.94
Y4	Third	First	Second	490.37
Y5	Second	Third	First	440.17
Y6	Third	Second	First	373.55

For a more in-depth and intuitive analysis of the data in Table 2, obtain the corresponding water pressure envelope curve of combination Y1–Y6 as shown in Figure 4. The illustration of the water pressure envelope curve is completely consistent with the previous Figure 2.

Figure 4(a) shows the water pressure envelope curve of pump shutdown accident conditions in the order of primary pump, midway pump, and final-stage pump at equal intervals (combination number: Y1). Under this accident condition, the maximum pressure head caused by the action of the water hammer appeared in the final-stage pump with a value of 496.77 m. It was difficult to ensure the safe delivery of water due to the operation of water pipelines under over-pressure.

Figure 4(b) shows the water pressure envelope curve of pump shutdown accident conditions in the order of primary pump, final-stage pump, and midway pump at equal intervals (combination number: Y2). Under this accident condition, the pressure head of the water transmission pipeline remained at a relatively low level under the action of the water hammer, and the maximum pressure head appeared in the final-stage pump with a value of 331.02 m.

Figure 5(a) shows the water pressure envelope curve of pump shutdown accident conditions in the order of midway pump, primary pump, and final-stage pump at equal intervals (combination number: Y3). Under this accident condition, the maximum pressure head was maintained at a relatively low level as a whole in the areas below 150-m elevation, but at a relatively high level in the region above 150 m. The maximum pressure head caused by the action of the water hammer appeared in the final-stage pump with a value of 455.94 m.

Figure 5(b) shows the water pressure envelope curve of pump shutdown accident conditions in the order of midway pump, final-stage pump, and primary pump at equal intervals (combination number: Y4). There is little difference between this accident condition and that of combination Y3. The maximum pressure head caused by the action of the water hammer appeared in the final-stage pump with a value of 490.37 m.

Figure 6(a) shows the water pressure envelope curve of pump shutdown accident conditions in the order of the final-stage pump, primary pump, and midway pump at equal intervals (combination number: Y5). Under this accident condition, the maximum pressure head was maintained at a relatively low level as a whole in regions below 90-m elevation, but at a relatively high level in regions above 90-m elevation. The maximum pressure head caused by the action of the water hammer appeared in the final-stage pump with a value of 440.17 m.

Figure 6(b) shows the water pressure envelope curve of pump shutdown accident conditions in the order of final-stage pump, midway pump, and primary pump at equal intervals (combination number: Y6). Under this accident condition, the pressure head of the water transmission pipeline remained at a relatively low level under the action of the water hammer, with the maximum pressure head appearing at 373.55 m in the final-stage pump.

Based on the results of the transient hydraulic calculations above, it is known that changing the pump shutdown precedence of the other pumps when the primary pump is first turned off will have a larger impact on the results.

If the final-stage pump is preferentially shut down over the midway pump, the pressure value of the water transmission pipeline can be maintained within a relatively safe range.

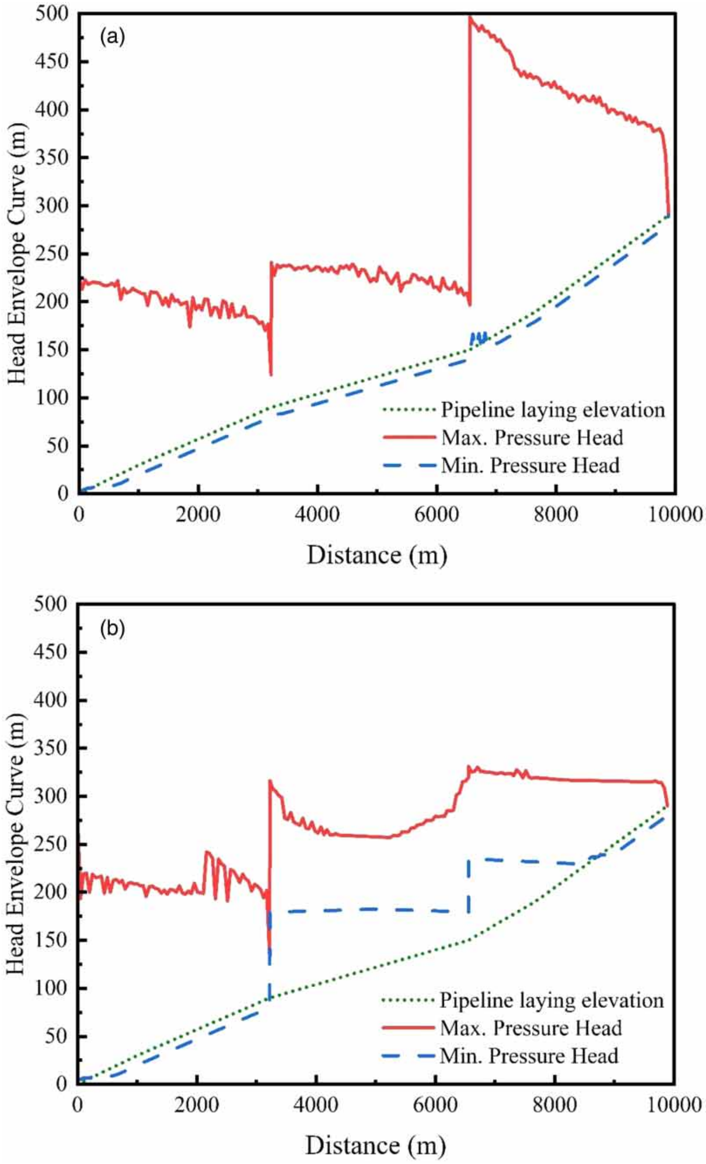


Figure 4 | Hydraulic envelope curve of combined processes: (a) Y1 and (b) Y2.

When the midway pump first shuts down, changing the pump shutdown precedence of other pumps will not have a larger impact on the calculation results, and it is difficult to maintain the pressure value of the water transmission pipeline within a relatively safe range under the action of water hammer, and its maximum pressure head value is very close to the 490 m of pressure head.

When the final-stage pump is shut down first, changing the pump shutdown precedence of other pumps will have a greater impact on the calculation results. If the midway pump is shut down preferentially over the primary pump, the pressure value of the water transmission pipeline can be maintained within a relatively safe range.

Regardless of the pump shutdown precedence, some sections of the water delivery pipeline were in a temporary state of negative pressure operation under the action of the water hammer, which is likely to cause the water hammer of cavities to collapse with water column separation. In practical engineering, such problems can be solved by using air vessels or air valves (Stephenson 1997; Izquierdo *et al.* 2006; Liu *et al.* 2012).

4.3. The impact of pump shutdown time

To evaluate the impact of pump shutdown time difference on the results of transient calculation, it is necessary to control the pump shutdown duration within a more appropriate range. According to the previous description,

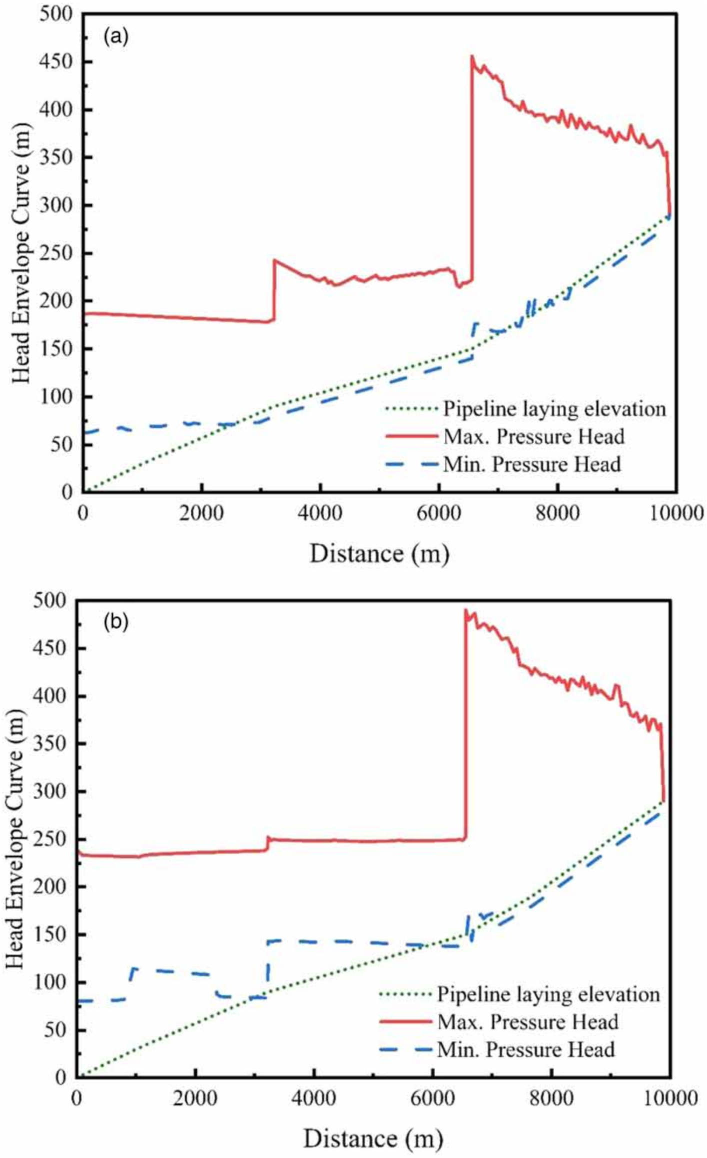


Figure 5 | Hydraulic envelope curve of combined processes: (a) Y3 and (b) Y4.

when the pump shutdown time is less than the duration of the water hammer, the type of water hammer is a direct water hammer.

Due to the greater harm of direct water hammer to the water delivery system compared to indirect water hammer, the influence factor of pump shutdown time could be exerted to reduce the harm level. Therefore, the total length of the water pipeline of 10 km and wave velocity of 1035.17 m/s, t_w is calculated to be 19.1 s (Equation (1)). The pump shutdown duration is then controlled to be within the range of 19 s. In the following experiments, the transient calculations were sampled at a frequency of 1 s. The specific reasons are as follows:

- In practical engineering, the minimum limit for PLC equipment used for the remote control of pump start and stop time is 1 s.
- Based on the premise of incomplete understanding of the optimal results, using the 1-s average screening test results is the most reliable method. Although this method is not a more accurate method, it is useful for reaching the best possible results by intuitively distinguishing the approximate impact trend of pump shutdown time difference on transient calculations and determining the effective test range.

Considering the high randomness of pump shutdown accidents in multi-stage series booster pump stations, and the use of a reasonable pump shutdown sequence as a control method cannot be effective for all randomly

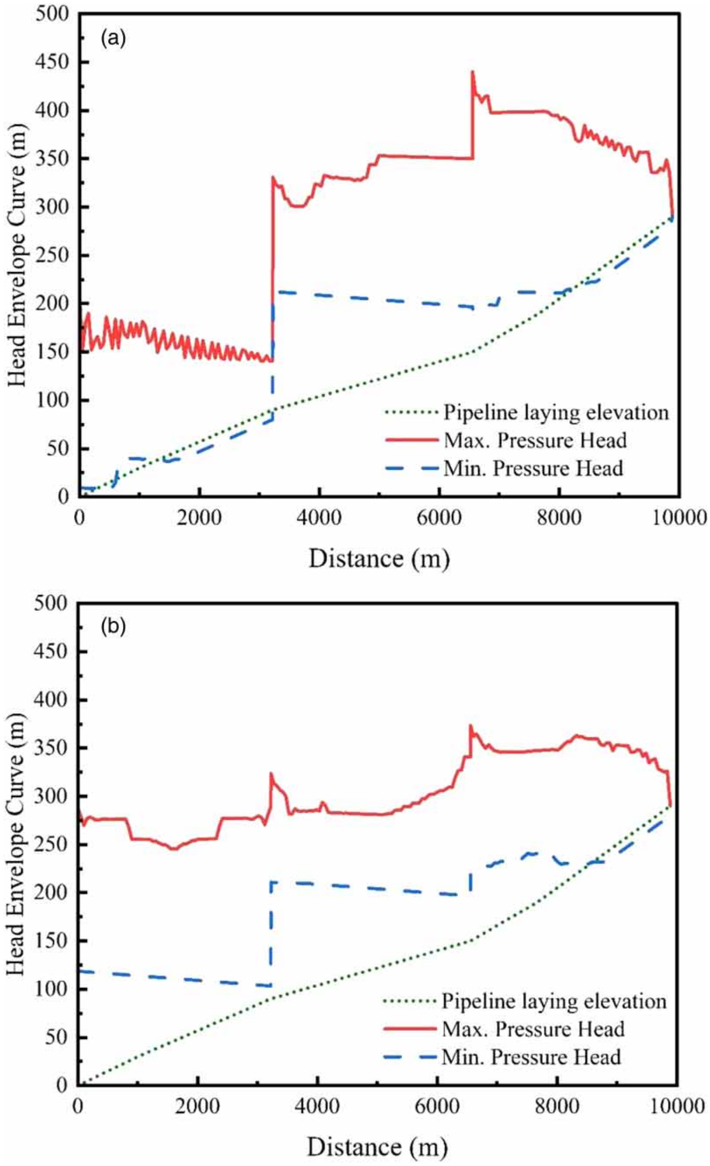


Figure 6 | Hydraulic envelope curve of combined processes: (a) Y5 and (b) Y6.

triggered accidents, so it is necessary to introduce pump shutdown time difference as a control variable for global analysis.

4.3.1. Assuming a shutdown accident occurs at the primary pump

To verify the impact of pump shutdown time difference on transient hydraulic calculation, it is assumed that a pump shutdown accident occurs at the primary pump station near the water intake point. A total of 361 combinations were obtained with the pump shutdown time as the control variable and the total pump shutdown duration of 19 s as the control quantity.

These combinations were numerically simulated using software without the use of any water hammer protective equipment. After the transient hydraulic calculation, the maximum pressure head values of all combinations were summarized in Supplementary material, Table S1.

For further analysis and verification, a total of 361 data items (combination numbers Z1–Z361) were extracted from Supplementary material, Table S2, and a three-dimensional mapping surface diagram is shown in Figure 7 was established. The two horizontal axes are represented by the primary pump and final-stage pump shutdown time, and the vertical axis is represented by the maximum pressure head. The data in the table can be divided into three sections based on the pressure head of 400 m of pressure head and 490 m of pressure head: pressurization section, high-pressure section and fluctuation section.

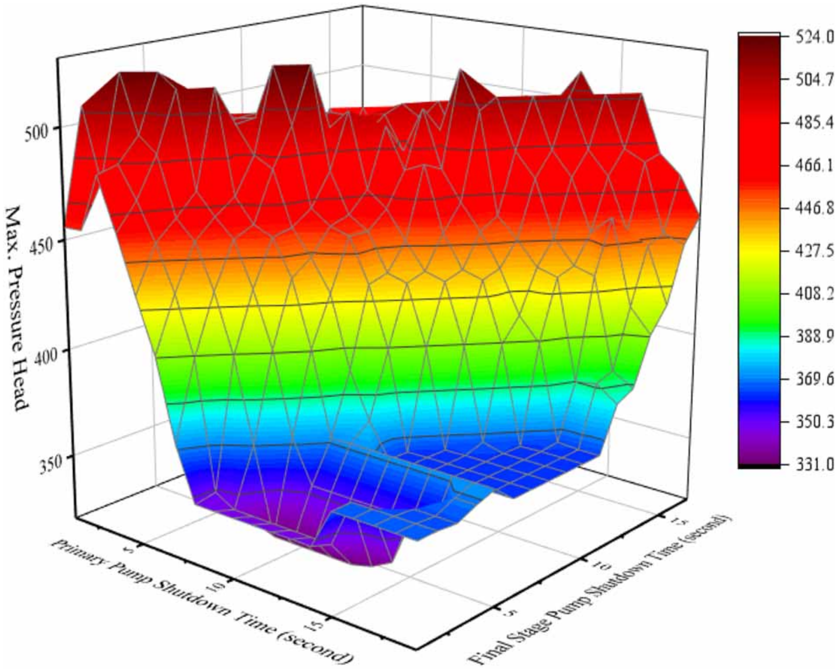


Figure 7 | Relationship between pump shutdown time and maximum pressure head (combination Z1–Z361).

Among them, the pressurization section is enclosed with a dashed frame, and the data in the lines are all below 40-bar pressure. At this time, the water transmission pipeline is able to work normally. The high-pressure area is enclosed with a solid wire frame, in which the working pressure is above 490 m of pressure head. There is a risk of damage to the water supply pipeline at any time during this situation. The other data that is not completely surrounded by the wireframe belongs to the fluctuation zone, and the pressure heads within this range are maintained between 400 m of pressure head and 490 m of pressure head.

Within 19 s after the shutdown accident of the primary pump, the final-stage pump was normally shut down first, with an interval of 4–6 s, and then the midway pump normally was shut down to maintain the pressure head in the pressurization section. On the contrary, if the midway pump is shut down normally, with an interval of 4–6 s, and then the final-stage pump is shut down normally, it will stabilize the pressure head in the fluctuation section and high-pressure section, posing a great threat and challenge to the safety of the water transmission system. It is further explained to which interval the section of the maximum pressure head is assigned in the results of the transient hydraulic calculations, depending on the precedence of the pump shutdown. The influence of pump shutdown time can cause the maximum pressure head in the transient hydraulic calculation results to change in a small range over an interval section. In addition, considering the extremely low probability of pump shutdown accidents occurring simultaneously in multiple pump stations in practical engineering, the total number of pump shutdown has a much smaller impact on the water hammer effect than the other two influencing factors, and can therefore be ignored.

Furthermore, the influencing factor of pump shutdown precedence plays a role in allocating the maximum pressure head section to which section in the transient hydraulic calculation results, when a pump shutdown accident occurs at the primary pump station. And it is the main influencing factor affecting the transient hydraulic calculation results. The influence factor of pump shutdown time difference plays a role in controlling the small fluctuation of the maximum pressure head value within a certain range in the transient hydraulic calculation results, so it is a secondary influencing factor that affects the transient hydraulic calculation results.

4.3.2. Assuming a shutdown accident occurs at the midway pump

Assuming a pump stop accident occurs at the pump station midway as a prerequisite, the pump shutdown time of the primary pump and the final-stage pump were used as control variables, and the pump shutdown duration was used as control quantification. Then a total of 361 pump combinations with different pump shutdown times were calculated, as shown in Supplementary material, Table S2.

It is known that there was no substantial change in the maximum pressure head value that appeared in the water transmission pipeline within 19 s after the first pump shutdown accident occurred in the midway pump, regardless of when the primary pump shutdown. This further indicates that the shutdown time of the final-stage pump is the only variable that affects the results of the transient hydraulic calculations.

For further analysis and verification, a total of 361 data items (combination numbers Z362–Z722) were extracted from Supplementary material, Table S2, and a three-dimensional mapping surface diagram is shown in Figure 8 was established. The two horizontal axes are represented by the primary pump and final-stage pump shutdown time, and the vertical axis is represented by the maximum pressure head. It was found that when the shutdown time of the final-stage pump was less than 4 s, the maximum pressure head increased significantly in a relatively short period of time, reaching a maximum value of 502.92 m in the fourth second, an increase of 23.7%. Subsequently, from the fourth second to the seventh second, the maximum pressure head remained basically within the pressure head range of 490 m or more, until it began to decrease at the eightth second and dropped to the minimum value of 455.94 m at the tenth second, with a decrease of 8.5%. When the shutdown time of the final-stage pump exceeded 10 s, the maximum pressure head fluctuated up and down in the pressure head range of 460–480 m, ultimately stabilizing.

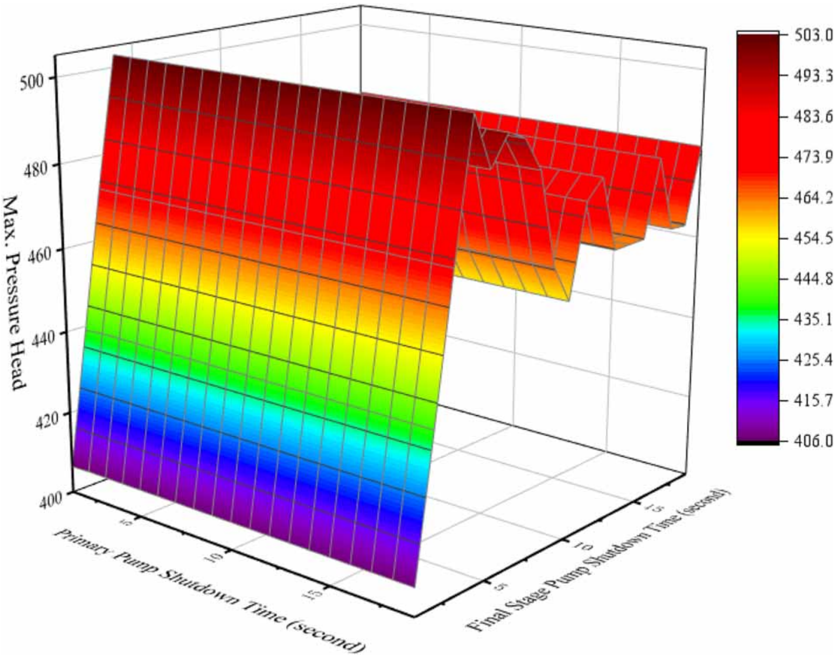


Figure 8 | Relationship between pump shutdown time and maximum pressure head (combination Z362–Z722).

In view of this, the relationship point-line chart can be divided into three sections:

- Pressurization section: the final-stage pump shutdown time from first second to fourth second.
- High-pressure section: the final-stage pump shutdown time from fourth second to seventh second.
- Fluctuation section: the final-stage pump shutdown time from eighth second to 19th second.

It is difficult to apply the method of adjusting the shutdown time of the final-stage pump to control the pump shutdown accidents caused by the midway pump without considering any water hammer protective equipment, due to the absence of a front low-pressure section in the relationship point-line chart. It can be confirmed that the occurrence of pump shutdown accidents can be avoided as much as possible by using appropriate water hammer protection devices (Jung & Karney 2008; Mohammad *et al.* 2019; Arefi *et al.* 2021). The specific reasons are as follows:

- Only by adjusting the pump shutdown time to the pressurized section before the high-pressure section can the impact of the high-pressure water hammer on the water transmission pipeline be effectively avoided, but the pressurization section cannot provide sufficient adjustment space due to its ‘short time’ and ‘fast pressurization’ characteristics.

- The minimum pressure head value in the relationship curve is 406.46 m. At the same time, it is necessary to ensure that the pump shutdown time is controlled within 1 s. It can be assumed that there is a smaller pressure head value at a certain instant within 1 s. In theory, the pump shutdown time can also be adjusted to this instant, but based on the current technical level, it cannot be applied to practical engineering.

4.3.3. Assuming a shutdown accident occurs at the final-stage pump

In the event of a pump stop accident occurring in the final-stage pump station, the same experimental control method as above will be used, a total of 361 pump combinations with different pump shutdown times were calculated, as shown in Supplementary material, Table S3.

From the data in the table above, it can be seen that within 19 s after a pump shutdown accident occurred in the final-stage pump station, the normal shutdown time of the primary pump station has little impact on the transient hydraulic calculation results. For further analysis and verification, a total of 361 data items (combination numbers Z723–Z1083) were extracted from Supplementary material, Table S3, and a three-dimensional mapping surface diagram is shown in Figure 9 was established. The two horizontal axes are represented by the primary pump and final-stage pump shutdown time, and the vertical axis is represented by the maximum pressure head. It was found that adjusting the shutdown precedence of the primary pump station and the midway pump station cannot effectively reduce the transient hydraulic results, contradicting the previous inference results. This indicates that the normal shutdown time of the midway pump station is the main factor affecting the results of transient hydraulic calculations.

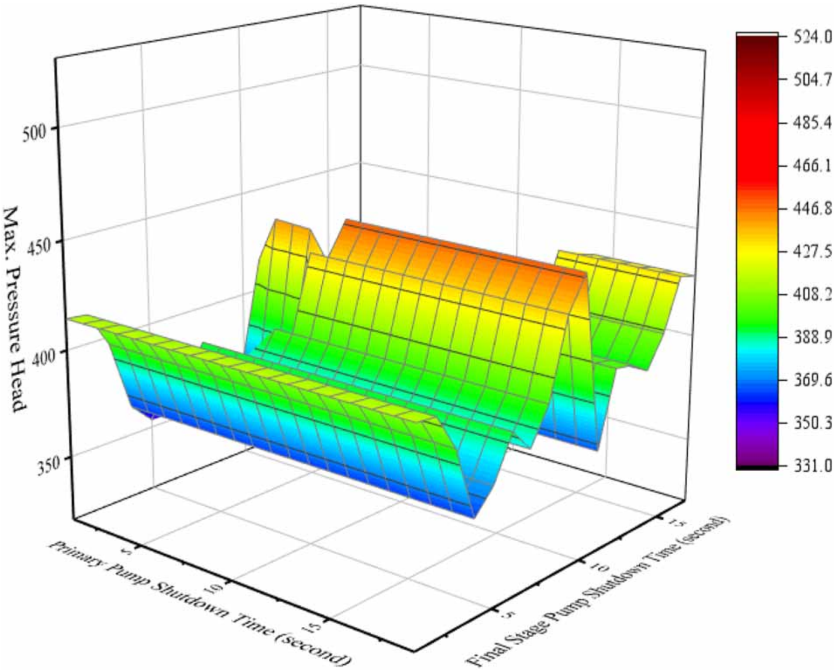


Figure 9 | Relationship between pump shutdown time and maximum pressure head (combination Z723–Z1,083).

To further analyze the impact of this variable on the transient calculation results, all the water hammer calculation results in the table are divided into two regions, with the boundary between the two regions represented by wave lines. The position of the zigzag line is set between the eighth second and the ninth second during the normal shutdown of the midway pump station. When the normal shutdown time is controlled within 8 s, the maximum pressure head will not exceed 414.50 m regardless of the primary pump station shutdown time. If the normal shutdown time of the midway pump station is postponed after the ninth second, regardless of when the primary pump station is shut down, the maximum pressure head that appears in the statistics is 448.76 m.

Based on this, the maximum pressure head appearing in the right area of the wave break line in the table is 1.083 times larger than that of the left area of the wave break line. This further indicates that adjusting the normal shutdown time of the midway pump station can theoretically reduce the maximum pressure head of the water transmission system by 7.6% in case of water hammer accidents.

In summary, when a pump shutdown accident occurs in the final-stage pump station, the normal shutdown time of the midway pump station is the main influencing factor on the results of the transient hydraulic calculation, but the impact effect is very limited and can only be used as an auxiliary means. However, adjusting the normal shutdown time of the primary pump station and adjusting the shutdown precedence of other stage pump stations are not sufficient to have a substantial impact on the results of transient hydraulic calculation.

5. CONCLUSIONS

This article conducts a study on the possible shutdown accidents in long-distance water transmission systems in mountainous areas that use cascade pump stations for pressurization. The main conclusions were summarized as follows:

- The more pump stations are shutdown abnormally, the more severe the impact of the water hammer on the water transmission pipeline.
- It is impossible to avoid pump shutdown accidents in the middle of the pumping station by scheduling the pump shutdown precedence and time difference of other stage pump stations.
- The operation of adjusting the pump shutdown time difference can serve as a PLC auxiliary means to co-operate with the water hammer protection during the shutdown of the edge pump station.

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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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