Research on water hammer protection for a long-distance water supply system of a deep well pump group

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Abstract. This paper is based on the hydraulic characteristics of the multi-pump group, high head, and small flow of a long-distance water supply system in a deep well pump group. Firstly a calculation analysis model is established, and then a non-water hammer protection measure is carried out for its typical controlled working condition system. The pressure distribution characteristics of the water supply system reveal that the hydraulic transition process of the water supply system of the deep well pump group is even worse. Then, according to its hydraulic characteristics, a cost-effective water hammer protection measure-a one-way surge tank and air valve combined protection plan was selected. Finally, the calculation and analysis of the hydraulic transition process of setting the system one-way surge tank and air valve joint protection plan are carried out. The calculation results show that the one-way surge tank and air valve combined to protect water hammer have a good effect on this water supply system. It provides a new idea for the water hammer protection setting of the long-distance water supply system of the deep well pump group with high water head and small flow.

1. Introduction
In the long-distance water conveyance project based on multi-pump group, when the multi-pump group stops the pump accidentally at the same time, it is very likely to cause the pressure drop to the gasification pressure of the liquid in the pressurized pipeline, which causes the gasification of the transported liquid and produces holes. Liquid column separation occurs when cavitation fills the whole section of the pipeline. When the formed cavity is annihilated, the water vapor in the cavity condenses rapidly due to the bridging of two water columns, resulting in the violent collision of the originally separated water column and a strong boost. Moreover, this pressure fluctuation will continue to spread along the pipeline, which has a serious impact on the normal operation of water conservancy facilities along the pipeline. With the continuous improvement of water conveyance safety requirements for long-distance water supply projects, the research on hydraulic transition process has become increasingly important. In this paper, based on the long-distance water supply system of deep well pump group, HysimInt software is used for modeling and analysis. In view of its unique hydraulic characteristics, the combined protection scheme of one-way tower and air valve in main and branch pipes is selected, which can provide reference for the analysis of hydraulic transition process and water hammer protection design of similar water supply projects.

2. Profile of Project
In a water supply project in Africa which the water source is groundwater, the groundwater depth of the intake well is 56m~75m. The installation elevation of 12 deep well pumps is 120m~140m underground
and the design flow rate of a single pump is 200 m³/h or 300 m³/h. The 12 deep well pumps (MV1~MV12) jointly supply water to the forebay of the PS2 pump station. The length of the branch pipes of the pump group is about 30 m~50 m, the pipe diameter is 0.15 m or 0.18 m, the total length of the main pipe is 7.7 km, and the pipe diameter is 0.3 m~0.8 m. The total flow of water supply is 3300 m³/h. The layout of the deep well pumping station group is shown in Figure 1, and the topography of the main line and the initial water pressure line are shown in Figure 2.

This project has the typical characteristics of high water head and small flow. In addition, due to the large number of pumps and relatively even distribution along the pipeline, if multiple pumps are powered off at the same time, they will show multiple decompression waves superimposed on each other in the system, which is likely to cause water hammer of cavities collapsing [5-7]. Therefore, it is necessary to determine the appropriate water hammer protection method according to its characteristics of water hammer by systematic analysis and research.

3. Mathematical Model And Software For Calculation

The overall structure of the whole system model adopts the structural matrix method [8], and the core algorithm adopts the classical characteristic line method to process the pipeline system [9]. In this paper, only the mathematical model of one-way surge tank is explained. As an economic water replenishing equipment, the one-way surge tank is permanently located in the parts where are easy to cause negative pressure. It is composed of the tower body and auxiliary branch pipes, valves, etc. The tower body is connected to the main pipe of the pump station through a check valve, and the opening and closing of the check valve is controlled by the pressure of the outlet pipe: when the water pump is started, the check valve is closed, and the tower is filled with water immediately through the water supply pipe; When the water level reaches the design water level, the float valve at the outlet of the water supply pipe is closed to maintain automatically the design water level in the tower. After the pump is stopped in an accident, when the pressure of the outlet pipe drops to the designed water level in the tower, the check valve opens quickly, and water is supplied immediately to the main pipe through the auxiliary branch pipe to prevent the pressure drop in the pipe from causing water column separation [10]. Its structural form is relatively flexible, concrete structure, steel structure and other material types which meet the requirements can be used.

Figure 1. The general layout of the deep well pump group water supply system.

Figure 2. The diagram about topography of the main pipe in the deep well pump group water supply system and the steady-state operating water pressure line.
The control equation of hydraulic node in one-way surge tank includes the flow continuity equation:

\[ Q_{p2} = Q_{st} + Q_{p1} \]

(1)

The balance equation of water head:

\[ H_p = Z_{st} - R_k Q_{st} |Q_{st}| \]

(2)

The relationship between flow and water level:

\[ \frac{dZ_{st}}{dt} = -Q_{st} / A_{st} \]

(3)

The compatibility equation of pressure pipe:

\[ H_p = C_{p1} - B_{p1} Q_{p1} \]

\[ H_p = C_{M2} + B_{M2} Q_{p2} \]

(4)

In the formula, \( Z_{st}, A_{st} \) represents the water level and cross-sectional area of the one-way surge tank; \( Q_{st} \) represents the flow out of the connecting pipe of the one-way surge tank, \( Q_{st} \) is positive when it flows out and it flows in one direction; \( R_k \) represents the head loss coefficient of one-way check valve which is related to the opening of one-way check valve; \( H_p, Q_{p1}, Q_{p2} \) represents the transient head and flow of pipeline boundary. Considering that \( \Delta t \) in water hammer is very small, the equations (2) and (3) can be simplified as:

\[ Z_{st} = Z_{st0} + 0.5\Delta t(Q_{st} + Q_{st0}) / A_{st} \]

(5)

\[ H_p = Z_{st} - R_k Q_{st} |Q_{st0}| \]

(6)

In the formula, \( H_{st0}, Q_{st0} \) represents \( H_{st}, Q_{st} \) of the previous time step. It can be deduced from equations (1), (4) and (6) that:

\[ H_p = (C_1 / C_2 + C_{p1} / R_{p1} + C_{M2} / R_{M2}) / (1 / C_2 + 1 / R_{p1} + 1 / R_{M2}) \]

(7)

In the formula, \( C_1 = Z_{st0} + 0.5\Delta t Q_{st0} / A_{st} \); \( C_2 = R_k |Q_{st0}| + 0.5\Delta t / A_{st} \). Other transient values can be determined after \( H_p \) is calculated through the equations (7).

The calculation software adopts HysimCity, a calculation and analysis software for water hammer protection in long-distance water supply systems developed by POWERCHINA HUADONG ENGINEERING CORPORATION LIMITED which owns all intellectual property rights. This software is written based on the theory of elastic water hammer and has been applied in many water supply projects. For pipeline layout of the water conveyance system, the initial pipeline calculation model established by the calculation software HysimCity is shown in Figure 3.
4. Calculation And Analysis Without Protective Measures

Case 1: The deep-well pumps are operated respectively at the normal groundwater level. The water level of forebay in pumping station is 897.3m. The 12 deep-well pumps are operating normally and stably. At a certain moment, all the pumps are powered off at the same time, and the valves after the pumps are closed quickly; The envelope of maximum piezometric head and minimum piezometric head along the pipe line of the deep well group is shown in Figure 4.

According to Figure 4, it can be seen that when there is no water hammer protective measure, the check valve after the pump closes immediately after the pump is powered off, which causes the pressure behind the pump to drop rapidly and produces pump-stopping water hammer. The negative pressure propagates downstream, and the negative pressure of almost the entire main pipeline is seriously exceeded: the maximum negative pressure of Case1 near pile number 0+100m reaches -289.5m (water column separation is not considered in calculation, which is actually seriously gasified. The greater the negative pressure, the more serious the water column separation, and the greater the positive pressure generated during the water hammer of cavities collapsing. The main reason for such a low pressure is the superposition of surge waves due to the different positions of the main pump station group, the same reasons as below). At the same time, the negative pressure of the rear lift pipe and the branch pipes of the deep well pumps are seriously exceeding the standard. If proper water hammer protective measures are not taken, the power failure of the pump will cause the water column separation, and the negative pressure generated may lead to instability and deformation of steel pipe under external pressure. If the water column is separated and the water hammer of cavities collapsing is generated, it may cause a pipe burst accident which threatens the safety of the pipeline operation and the stability of the water supply [11]. Therefore, reasonable water hammer protective measures must be taken to control the water hammer when the pump is stopped to protect the safety of pipeline operation.

5. Protection Combined With One-way Surge Tank And Air Valve

According to the characteristics of the deep well pump layout of the project, the water pump installation elevation below the ground is between 120m–145m, and the pump head is between 110–160m. After analysis and optimization, 20 air valves are installed in the water supply pipeline of the one-way surge tank combined with air valve water hammer protective plan, and each air valve is installed on the water lift pipe after the check valve of the deep well pump, with a valve diameter of DN25; There are altogether 8 air valves at the high point of the main pipeline, and the valve diameter is DN50~100. MV1~MV12 deep well pump is equipped with a one-way surge tank after the check valve which height is 6m, the
The cross-sectional area is 3m², and the initial water level is 50cm from the top of the tower. The calculation model of the one-way surge tank + air valve joint protection is shown in Figure 5.

In the above optimized one-way surge tank tower + air valve joint protection plan, when 12 deep well pumps are cut off at the same time (Case1), the check valve behind the pump and the check valve in the pump house will be closed instantly [12]; In order to prevent the water in the one-way surge tank from being drawn out, an automatic adjustment valve is set at the end. The valve is closed when the pump is powered off. The closing rule is closed by two broken lines: the total closing time is 120s, in which the valve opening of the first 60s is closed to 0.15, and the valve opening of the latter 60s is closed to 0.

Figure 5. The calculation model of one-way surge tank + air valve joint protection.

When it takes one-way surge tank tower + air valve joint protection plan, the valve after each deep well pump is a quick-closing check valve; The pump has no reversal after power failure; The maximum and minimum pressure of the lift pipe behind pumps meet the control standards; The maximum and minimum pressure of the branch line of deep well pump meet the design requirements; The maximum pressure of the main pipeline is 60.4m while the minimum pressure is -4.4m, both of which meet the design requirements.
6. Conclusion
Through calculation of water hammer-free protection measures for a long-distance water supply system of a deep-well pump group, it was found that due to the multi-point distribution of deep-well pumps along the main line, the water supply system showed multiple surge waves superimposed when all deep-well pumps were powered off at the same time. The water hammer is worse under this working condition; in view of the characteristics of deep well pump group layout, high lift and small flow, each deep well pump branch line is selected to set up small-scale and low-cost one-way surge tank to reduce the amplitude of surge waves propagating to the main pipeline and reduce the impact on the main pipe. Air valves are set on the local raised parts of the main line to ensure that the minimum pressure value of the main line maintain a controllable range and to ensure the safety of the water supply system. The joint protection plan of setting one-way surge tank on branch lines and setting air valves on main and branch pipes provides a new idea to solve the water hammer protection of deep well pump group water supply system with high head and small flow.

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