Numerical simulation of hydraulic optimization for regulating tank in pumping station

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Abstract. Based on the governing equations of steady incompressible fluid, renormalization group (RNG) turbulence model and SIMPLEC algorithm are used to calculate the steady flow field of regulating tank in the pumping station with six different geometries operating under same condition. The impacts of the layout schemes of guide walls for the flow field of the regulating tank are analyzed. The numerical results are verified by physical model experiment and good agreement is found. The results show that: 1) serious flow separation of side wall will occur in the regulating tank when the interval of diversion wall is 10 L; 2) the flow velocity in the regulating tank will be too low when the diversion wall spacing is 16 L; 3) the improvement of the flow pattern of the regulating tank is not obvious; and the project cost is increased when the excavation depth of the regulating tank is increased by 1 m; 4) the bottom velocity reached the non-silting velocity and the head loss of the regulating tank reducing nearly 1.2 m by using arrangement form of wide 21 L and narrow 10L of the guide walls, which provides a certain guarantee for the safe operation of the pumping station. The regulation tank layout scheme proposed in the paper can be applied to engineering practice.

Keywords: Guide wall, Numerical simulation, pumping station, Regulating tank

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1. Introduction

Regulating tank is widely used in water supply and drainage system, and its application varies in different fields. As clear water supply is the main priority in our life [1-5], water tower and clean water
tank in the water supply system; and storage tank in the building water supply system are broadly discussing [6-7]. All water tanks are categorized as regulating pool [7-9].

A pumping station in Shanghai does not belong to the hydraulic structure of water supply and drainage system, but it is an engineering design which includes regulating tank. There are two main functions of a regulating tank. Firstly, it is an important measure to ensure uninterrupted raw water within a certain period of time when carrying water from the Huangpu River. Since water usage may vary from day to night and from day to day, the regulating pool/tank can improve the safety of water supply. Secondly, the regulating pool/tank together with diversion wall can be set up to ensure no sediment deposition in the water transport buildings (it is because sediment and other impurities in the water can flow from the water source), so that, the flow of the channel reaches the non-silt flow rate.

In recent years, with the development of computer technology and computational fluid dynamics theory, hydrodynamic model and Computational Fluid Dynamics (CFD) model are becoming an important tool to understand the flow status of water [10-15]. COD model has been applied by many researchers and achieved many certain results [10-12]. Research on the regulating tank mainly focuses on the design [16-18], and does not consider the influence of the flow pattern inside the regulating tank. In order to ensure the safe and stable operation of the pumping station, a reasonable layout of the diversion wall is very important. This study tries to find a reasonable layout of the diversion wall through numerical test. Therefore, this study applied the computational fluid dynamics software ANSYS Fluent and RNG $k-\varepsilon$ turbulence model to carry out CFD calculation on the whole model of a Shanghai pumping station with multiple diversion wall arrangement schemes under typical water level conditions. A reasonable diversion wall layout which flows pattern is optimal and hydraulic loss is minimum will be sought by comparing and analyzing the change of water flow pattern and hydraulic loss between different diversion wall layout schemes. This paper can provide some reference for the optimization design of similar project.

2. Materials and Methods

2.1 Calculation model and schemes

In this study, a pumping station in Shanghai is considered as the study area. The calculation model which includes the water distribution pipe, regulating tank, forebay, water inlet tank and water pump suction pipe as shown in Figure 1. In order to fully analyze the influence of the layout of diversion wall on the distribution of flow pattern and the change of head loss, six different layout forms of diversion wall are selected for calculation under typical water level conditions. Specifically, a number of diversion walls are arranged in the regulating pool to form a preliminary design scheme (scheme 1). Scheme 2 appropriately widens the flow channel on the basis of the scheme one. Scheme 3 adjusts the flow direction according to the scheme two. Scheme 4 enlarges the excavation depth base on the scheme three. Scheme 5 improves the flow pattern in the dead water area on the basis of the scheme 4, and scheme 6 further adjusts the size and spacing of diversion wall. The six layout plans of diversion walls are shown in Figure 2.
2.2 Calculation method and grid division

The flow in the regulating tank is turbulent and the flow is quite complex. However, under the assumption of continuous medium, the motion of fluid can be described by continuous equation and Navier-Stokes equation.

The equation of continuity:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

(1)
And the equation of N-S:

\[ \rho \frac{\partial \mathbf{u}_i}{\partial t} + \rho \mathbf{u}_j \frac{\partial \mathbf{u}_i}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 \mathbf{u}_i}{\partial x_j \partial x_j} \]  \hspace{1cm} (2)

In the formula, \( \mathbf{u} \) is the fluid velocity vector; \( \rho \) is the fluid density; \( f \) is the mass force; \( p \) is the pressure; \( \mu \) is the turbulent viscosity.

It is generally considered that water flow is an incompressible fluid and the heat exchange capacity is very small, so the energy conservation equation is not considered. The Reynolds averaged N-S equation is used to describe the turbulent motion, which is not close. It is necessary to introduce turbulence model for understanding the equations. In this paper, RNG k-\( \varepsilon \) model is used to simulate the flow characteristics in the computational domain.

The fluid domain mainly includes water distribution pipe, regulating tank, forebay, inlet channel and outlet pipe. In numerical calculation, grid is not only an indirect expression of geometric model, but also an important carrier of numerical calculation and analysis. The quality of grid directly affects the accuracy and efficiency of calculation, as well as the correctness and reliability of calculation results. There are many flow diversion walls in the whole channel of the regulating pool, and the geometric layout is complex. Considering the complexity of the layout of the regulating tank, the unstructured tetrahedral grid with strong geometric adaptability is divided by using the grid generation software ANSYS ICEM to locally encrypt the grid at the turning of the water flow, and the overall grid is shown in Figure 3. According to the analysis of grid independence, the total number of grid elements in the flow calculation domain of the whole midway pumping station is 9.91 million.

Figure 3. Mesh division of the pump station model.

2.3 Discretization of equations and boundary conditions

In the numerical simulation of a pumping station model in Shanghai, the water speed at the entrance area is adopted at the entrance boundary while the size and direction of the speeds are given. The outflow condition is adopted at the exit boundary, in other words, the gradient of each transport variable on the exit section is zero. For free/open water surface, it is assumed to be free stress boundary. The control equation is discretized by the finite volume method. Second order central difference scheme is adopted for diffusion term, and second order upwind scheme is adopted for convection term. The coupling of pressure and velocity adopts SIMPLEC algorithm.
3. Results and Discussions

3.1 Analysis of Flow Distribution

The geometric model of a pumping station in Shanghai as shown in Figure 1 is simulated using three-dimensional turbulence model. The calculated water level is 3.8m, and the starting combinations are 1# 2# and 4#. Figure 2 (a) to Figure 2 (f) are selected for the arrangement forms of the regulating tank. The spatial streamline distribution diagrams of the six schemes correspondingly are shown in Figure 4 (a) to Figure 4 (f). Based on Figure 4, we can demonstrate that there is an obvious side-wall flow phenomenon in Scheme 1, which can easily cause serious siltation (Figure 4 (a)). The water flow in the inlet flume at the front of the pump station is obviously skewed to one side, thus inducing the deterioration of the water flow pattern in the forebay of the pumping station. As shown in Figure 4 (b), with the increase of the wall channel width, the water flow pattern does not change substantially. The phenomenon of off-flow and backflow in the inner wall of the channel is more obvious, and even a small area of vortex appears. There is still serious flow deviation at the inlet of the forepool. In Figure 4 (c) and Figure 4 (d), the flow pattern in the regulating tank is roughly similar, and the flow pattern at the overflow weir is relatively good, followed by serious side-wall outflow. In Figure 4 (e), the flow pattern in the regulating tank is improved, and the initial flow pattern of the front-end channel in the front pool is good, but the flow pattern distribution becomes worse when it enters the forebay. In Figure 4 (f), the spatial streamline distribution is good, and the side-wall off-flow phenomenon is significantly improved, especially the water flow in the forebay is in the center, which is helpful to optimize the water flow pattern in the pump sump of the pumping station.

![Spatial streamline distribution diagram of six schemes.](image-url)
Figure 5. show diagrams of the velocity distributions at the bottom area for six schemes (a) to (f). It can be seen that the bottom velocity of waters in Figure 5 (a) to Figure 5 (e) reaches the non-silting velocity. However, there are various degrees of water bias in the front channel of the forepool, which is not conducive to the efficient and stable operation of the pumping station. In Figure 5 (f), the numerical results show that layout of Scheme 6 effectively homogenizes the flow distribution of the channel and improves the flow pattern of the regulating tank.

3.2 Analysis of Hydraulic Loss
In order to verify the accuracy of the numerical simulation study on the flow state of the regulating pond and the hydraulic loss of the inlet system, a physical model test is carried out for optimization scheme of the numerical simulation calculation as shown in Figure 6. The whole normal hydraulic model is used in the model test of the pumping station, which is designed according to the gravity similarity criterion. The model includes the inlet pipe, regulating tank, forebay, sump and outlet pipe. Considering the requirements of the model water flow in the resistance square region and the selection of the model pump, the model linear scale $\lambda_l=10$ is intended to be selected. According to the test and research requirements of the pumping station, the water pump with similar geometry and flow suitable for the simulation requirements is used as the test pump.

After investigation and comparison in many aspects, the 150ZLDB vertical mixed flow pump is proposed to be used as the test pump, and the water flow rate of the pump is adjusted through the gate valve on the outlet pipe, so as to meet the test requirements. The regulating tank of the prototype are made of reinforced concrete which roughness is 0.013–0.014, and corresponding roughness of the model is 0.009–0.010. The side wall of the model bottom plate is finely painted with pure cement, and its roughness can reach 0.010. The pool partition and the inlet pool are made of plexiglass and plastic plates, with a roughness of about 0.009, and the model meets the requirements of similar roughness.
Figure 6. Physical test model of the pumping station.

Physical model tests were carried out on the above six diversion wall layout schemes of regulating tank, and the head losses of the six-diversion wall physical models were collected, counted and converted. The head losses were compared with those collected in numerical simulation results, as shown in Figure 7. Based in Figure 7, both curves show a decreasing trend and tend to overlap, indicating that the numerical simulation results are reliable. Among the six schemes, scheme 6 has the lowest hydraulic loss, which is nearly 1.20 m lower than scheme 1, indicating that the reasonable layout of diversion wall can not only optimize the flow pattern, but also effectively reduce the hydraulic loss.

Figure 7. Comparison of head loss of each scheme in numerical model and physical model.

4. Conclusion

Based on the governing equation of steady incompressible fluid and the renormalization group turbulence model, this study calculates the three-dimensional flow in the regulating tank of the pumping station by using the SIMPLEC algorithm. Further, this study compares and analyzes the flow patterns of the regulating tank under different diversion wall for arrangement schemes. The calculation results show that optimizing the size spacing and layout direction of the diversion wall can effectively homogenize the flow distribution, improve the flow pattern, and reduce the hydraulic loss in the regulating tank. In this paper, scheme 6 is determined as the best diversion wall layout scheme, which
can be a certain reference for engineering construction. This paper only for a pumping station in Shanghai. A reasonable arrangement of regulating pool diversion wall is provided, and the improvement measures for side-wall off-flow and flow deviation are relatively simple, and the search for better universal and diversified improvement measures remains to be studied.

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