Experimental study on flow pattern in forebay pump station and rectification scheme

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Abstract. The joint construction of sluice stations in the coastal plain area is widely used, but due to the complex inflow conditions, it is easy to produce reflux, vortex and other undesirable flow patterns, which have extremely adverse effects on the operation of pumping station units. For a sluice station project into the flow pattern problem, the model test to optimize the flow pattern of the front pool of the pumping station, the pumping station forebay with additional flow isolation pier program. The study found that: rectification scheme, pumping station before the pool flow pattern has a more obvious improvement, 1#, 2# inlet flow uniformity distribution increased by 9% and 2%. There will be no obvious adverse effects on the inflow conditions of the sluice. The optimized scheme has better inlet flow conditions than the original scheme, and the proposed optimized scheme can provide reference experience for other similar projects.

1. Introduction

In order to reduce the construction cost of the coastal plain area gate hubs, such as the construction cost of the project area and migration investment. In these areas, symmetrical layout and asymmetrical layout are generally used in combination of two gate station layout scheme. In the actual operation and related research process, it is found that, influenced by the layout of the gate station, river alignment and unit operation, the front pool of the pumping station produces a serious low-speed zone, reflux zone and inlet vortex and other unfavorable flow patterns, and the uniformity of flow velocity distribution in the inlet section is poor, which affects the pumping station operation efficiency. In this regard, Fu.[1] took the bulkhead of the gate station hub as the research object and proposed the proposed length of the bulkhead and the calculation formula; Tan.[2] made a comprehensive evaluation of the length of the bulkhead; Lu.[3] proposed through the study that extending the length of the bulkhead can effectively move up the backflow area and reduce the transverse flow velocity of the inlet basin; Tian.[4] made a simulation of the front pool and inlet basin of Rupganj North drainage and irrigation pumping station in Bangladesh Using the normal model test to simulate, proposed that setting the bottom can in the front pool can effectively improve the front pool flow pattern; Li.[5] introduced the Chaodong good harbor hub by setting the guide pier and the middle partition pier with the water passage hole to connect the sectional gates and pumping stations; Luo.[6], Xu.[7] researched that extending the diversion pier can improve the flow pattern around the diversion pier and improve the uniformity of the flow velocity of the inlet channel. Xu.[8] and others,
using physical model tests to study the asymmetric gate station hub, concluded that the selection of suitable length guide piers, and the opening of holes in the guide strong to improve the inlet conditions of the pumping station.

In this paper, a model test is carried out on the characteristics of water flow in the inlet pool and sluice of the sluice hub pumping station, and the flow characteristics of the front pool of the pump station and the uniformity of the flow velocity distribution at the inlet of the channel are analyzed. The model test results are compared before and after, and the influence of pumping station rectifier measures on sluice drainage is analyzed.

This paper takes an asymmetric arrangement of the lock station hub project as an example, and conducts model tests on the water flow characteristics of the lock station hub pump station forebay and sluice discharge, analyzes the water flow characteristics of the pump station forebay and the uniformity of the flow velocity distribution of the flow channel inlet, and proposes optimized improvement measures. And the model test results of different schemes are compared to analyze the impact of pumping station rectification measures on sluice discharge.

2. Model

The research model is designed according to the normal model, following the gravity similarity criterion and the turbulent roughness zone friction similarity criterion. The geometric scale of the model is 30, and the roughness scale is 1.76. The prototype roughness is 0.011~0.017, and the prototype roughness is 0.016 calculated according to the similar scale. The model includes upstream and downstream channels, bridge piers, sluice gates, pumping stations and inlet and outlet pools, etc. The model length is about 25m, width 3-15m (Figure 1). The pumping station model does not affect the flow pattern of the premise, the model centrifugal pump, control valve and pipeline electromagnetic flowmeter are installed laterally in the appropriate inlet and outlet water channel below the opening, so as to control the pumping station model flow. Upstream and downstream water levels are tested using water level stylus, flow velocity is measured using VECTRINO acoustic Doppler point flow meter, and the water flow pattern is photographed on video, where the surface flow field suspended particles and time-delayed exposure method.

![Figure 1. Layout Plan of Model](image)

Original scheme: The overall scheme is the arrangement of the pumping station on the right side of the left sluice gate (Figure 2). The pumping station has 3 units, each with a design flow of 27 m$^3$s$^{-1}$ and a total discharge flow of 81 m$^3$s$^{-1}$. The inlet width is 7.50m, height is 4.20m and bottom elevation is -4.73m; the outlet width is 6.50m, height is 4.50m and bottom elevation is -4.37m. The sluice gate is equipped with a chest wall, the gate is a flat helicopter gate, the gate is arranged with 2 holes, each hole has a net width of 10m and the bottom elevation of the sluice gate is -2.00m. A pier is set between the pumping station and the sluice gate, with a total length of 20m and a top elevation of 4.0m.
Optimization program: After a variety of program demonstration proposed cross-flow pier opening program (Figure 2): (1) pier head optimization for the semi-circular head, radius of 1.5m. (2) cross pier set 4 orifices, hole height 2m, width 2m, hole spacing 1m.

Figure 2. layout of original scheme (unit: m)

Figure 3. Plan view of the optimized scheme of pier (unit: m)

3. Results and analysis

3.1 Model test conditions
The combination of model test conditions is shown in Table 1.

| Category        | Water level (m) | Flow (m$^3$s$^{-1}$) |
|-----------------|-----------------|----------------------|
| Pump station test | 2.2 inlet, 2.6 outlet | 81                   |
| sluice test     | 3.7             | 2.6                  | 190                  |

3.2 Analysis of flow pattern in forebay of pumping station
The experimental study found that: the head of the pier pier head around the flow is larger, around the flow velocity of 1.2 ms$^{-1}$, the flow direction is not correct, the pumping station before the pool flow brought adverse effects. 1 # pump before the backflow area, backflow influence width to 2 # near the front of the pump, backflow area of about 100m2. Pump station flow channel mouth section, 1 # ~ 3 # pump inlet section average flow velocity of 0.70, 0.75, 0.80ms$^{-1}$, where 1 # pump The flow velocity on the right side of the inlet is significantly larger than the flow velocity on the left side, and the flow velocity of the inlet of 2# and 3# pump stations is more uniform.

The experimental study concluded that the length of the bulkhead wall at the combination of the gate station has a greater impact on the flow pattern of the water inlet forebay of the pump station, and the setting of the bulkhead wall is effective for eliminating the backflow and vortex at the mouth of the flow channel on the side of the pump station, and the increase in length can improve the performance of the pumps on the side and make the forebay backflow area move upstream, but at the same time, it increases the range of the forebay backflow area and causes the phenomenon of partial flow. The analysis of the comparison study concluded that the length of the bulkhead pier 20m is more economically appropriate and does not need to be lengthened. However, only the use of the pier to improve the flow pattern into the pool is not enough, should also take other effective corresponding rectification measures. To this end, the optimization test tried a variety of rectification ideas, the use of open holes in the pier, from the lateral diversion of the way to destroy the right side of the pier backflow generation, so as to achieve the purpose of improving the flow pattern.
The optimization test study selected the effect of rectification under different opening methods, and finally proposed the optimization plan. The optimized scheme basically eliminates the backflow area in the inlet pool of the pumping station, and the average flow velocities of the inlet section of pumps 1# to 3# are 0.74, 0.73 and 0.76ms⁻¹, respectively, which are greatly improved compared with the original scheme. The flow pattern and flow velocity distribution in the front pool of different schemes are shown in Figure 4 and Figure 5.

In order to compare and analyze the rectification effect of the optimized scheme, the flow velocity distribution of the inlet section is introduced, and the uniformity of flow velocity distribution is calculated according to the flow velocity of each measurement point in the vertical direction, and the uniformity of flow velocity distribution can be obtained from Equation (1), as shown in Table 2.

\[
V_\mu = \left[1 - \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\frac{V_i}{\overline{V}} - 1\right)^2}\right] \times 100\%
\]  

(1)

Where: \(V_i\) is the velocity of each measurement point of the section, ms⁻¹, \(\overline{V}\) is the average velocity of the section, ms⁻¹, \(n\) is the total number of points; \(V_\mu\) is the uniformity of the velocity distribution of the section.

From the perspective of uniformity of flow velocity distribution, the optimized scheme has a greater improvement than the original scheme, in which the uniformity of flow velocity distribution of 1# and 2# inlet has improved by 9% and 2%.

Therefore, by comparing and analyzing the flow pattern, flow velocity distribution and uniformity of flow velocity distribution in the inlet section of the original and optimized solutions, the optimized
scheme can effectively reduce the area of the reflux area in front of the inlet pool, and the uniformity of flow velocity distribution of the inlet channel of the pump station unit is improved, and the flow pattern of the front pool is improved more obviously.

| Programme               | Uniformity of inlet flow rate distribution of different units $V_\mu$ |
|-------------------------|-------------------------------------------------------------------------|
|                         | 1# | 2# | 3#          |
| Original programme      | 81%| 84%| 93%         |
| Optimization scheme     | 90%| 86%| 93%         |

3.3. Analysis on influence of sluice inflow
The combination arrangement of sluice station and the increase of rectifier measures, especially whether the opening of the baffle pier will have a negative effect on the inlet flow of the sluice, has not been studied in this respect.

Experimental observation of the optimal scheme of inlet flow state, inlet section velocity distribution and overcurrent capacity. Comparison of flow state, flow velocity and overcurrent capacity of different schemes is shown in Figures 6 to 8. (1) Flow pattern: Due to the opening of the diaphragm pier, the inlet flow direction of the optimized scheme is deflected.

(2) Inlet section velocity distribution: the velocity distribution of the left side of the inlet gate is basically unaffected compared with the original scheme, and the uniformity of the velocity distribution of the right side gate is improved compared with the original scheme; (3) Overflow capacity: the optimized scheme is basically the same as the original scheme, and the integrated flow coefficient and the distribution law of $c/H_2$, and the fitting formula is shown in Equation (2).
(2)

\[ C = A \left( \frac{e}{H_2} \right)^n \]

Where: C is the integrated flow coefficient, A, n is a constant; e is the sluice gate opening. H2 is the downstream water depth (calculation reference surface is generally the bottom plate of the sluice).

The study shows that the opening scheme of the diaphragm pier, except for the effect on the flow pattern, is basically unaffected on the overflow capacity of the sluice gate. Therefore, it is feasible to adopt the optimization scheme of diaphragm pier opening in asymmetric sluice station project.

4. Conclusion
(1) Asymmetric gate station hub, the pumping station operation around the diaphragm pier is prone to swirl back area, the flow pattern is poor, affecting the unit operating efficiency, but also prone to induce the generation of water inlet vortex.

(2) Through the model test research, the length of the facility is suitable for the bulkhead, and the orifice on the bulkhead can effectively reduce or even eliminate the backflow area in the front pool of the pumping station and improve the inlet conditions.

(3) Through the experimental analysis, it is concluded that the impact of setting openings in the bulkhead on the overflow capacity of the sluice gate is small. The research results provide reference for similar projects.

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References
[1] FU Zongfu , GU Meijuan , YAN Zhongmin. Nanjing Shape and suitable length for guide wall of combined sluice -pump station project[J]. Water resources and hydropower engineering 2011,42(10):128-131.
[2] YU Yonghai, CHENG Bin. CFD simulation and optimization on inflow pattern of diversion and intake pumping stations with side-inlets[J]. Water resources and hydropower engineering, 2012, 43 (2): 72-75, 89.
[3] Lu Yinjun Zhou Wei Ming Yuemin Ding Guoying. Layout design optimization of integrated pumping station and sluice with numerical stream simulation[J] Journal of Drainage and Irrigation Machinery Engineering, 2014,32(11):963-967.
[4] Luo Can, Qian Jun, Liu Chao, et al. Numerical simulation and test verification on diversion pier rectifying flow in forebay of pumping station for asymmetric combined sluice-pump station project[J]. Transactions of the Chinese Society of Agricultural Engineering, 2015, 31(7): 100-108.
[5] XU Bo,GAO Chen,XIA Hui, et al. Influence of Geometric Parameters of Perforated Diversion Pier on Flow-rectifying Effect in Forebay of Sluice-pump Station Project[J]. Journal of Yangtze River Scientific Research Institute, 2019,36(02):58-62.
[6] YU Yonghai, CHENG Bin. CFD simulation and optimization on inflow pattern of diversion and intake pumping stations with side-inlets [J]. Water resources and hydropower engineering, 2012, 43 (2): 72-75, 89.