Flow Pattern Analysis and Rectification Measures of Box Culvert in Urban Rainwater Pumping Station with Oblique Pipe Culvert

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Abstract: In order to study the influence of oblique pipe culvert inflow on hydraulic flow characteristics of urban rainwater pumping station and explore effective rectification measures to improve bad flow pattern, based on computational fluid dynamics (CFD) method, box culvert flow pattern analysis and rectification measures research of oblique pipe culvert inflow urban rainwater pumping station are carried out. According to the bad inlet flow state, by designing and arranging 3 different rectification measures in the gate shaft, the improvement effect of each rectification measure on the inlet flow state and water distribution uniformity of the box culvert is analyzed and compared, and the best scheme is selected and verified by physical model tests. The research shows that the oblique pipe culvert inflow is easy to cause uneven flow distribution in each hole of the box culvert and adverse flow patterns such as deflection flow, backflow, vortex and the like, thus deteriorating the inflow state of the forebay and affecting the safe operation of the pumping station; The combined rectification measures of diversion piers, composite beams and short diversion piers arranged at the back can significantly improve the bad flow pattern at the gate shaft, box culvert and forebay inlet, and effectively improve the uniformity of flow distribution in each hole of the box culvert, wherein the imbalance of flow distribution in each hole of the box culvert is reduced to between ±0.03 and the uniformity of total flow distribution in the box culvert is improved to 0.905。" The research results of this paper can provide useful reference for the design of rainwater pumping stations in the same type of cities.
Keywords: urban rainwater pumping station; Box culvert; Flow pattern; Flow distribution; Rectification measures; numerical simulation

Research background

Rainwater pumping stations are mainly used to remove accumulated water in urban low-lying areas and rainwater pipeline systems, and play a key role in preventing urban waterlogging disasters. Due to the restrictions of urban planning, topography and pipe network layout, the urban rainwater pumping station covers a small area and its intake structure is relatively compact, which often makes it difficult to layout according to the requirements of good hydraulic conditions in the pump station design code, thus making it easy.

This will cause undesirable flow patterns such as vortex, backflow and drift in the intake building of the pump station, which will seriously affect the safe and stable operation of the pump station.

It is of great significance to improve the bad flow pattern in the intake buildings of urban rainwater pumping stations to ensure the safety and reliability of their operation.

Therefore, Research methods for improving intake flow state of pumping station mainly include physical model test and numerical simulation calculation. Compared with physical model test, numerical simulation calculation has low cost, short cycle and can obtain more abundant flow field information. Especially in recent years, with the rapid development of computer technology and the continuous improvement of computational fluid dynamics (CFD) method, CFD numerical simulation is recognized by more and more scholars.

Yes, it has become an important means to analyze hydraulic flow characteristics and study rectification measures in pumping station engineering. Gao Chuanchang et al For Tianshan First-Class Pumping Station The different rectifying schemes to be selected for the forebay and intake pond are numerically simulated, and the integral suitable for the forebay and intake pond of the pumping station is selected.

The applicability of turbulence model is analyzed for the forebay of a pumping station, and the diversion pier is developed using realizable and k - ε models.

Numerical simulation study on the optimal arrangement of vortex elimination: Establishment, etc

The flow pattern in the forebay of the forward intake pump station with Y shaped diversion piers is numerically simulated. The influence of geometric parameters of Y shaped diversion pier on the improvement of forebay flow pattern is simulated and analyzed. Zidan et al. used CFD technology in combination with field tests.

In this paper, the rectification optimization research of the combined diversion pier in the inflow field of large pumping

station is carried out, and the inflow of the combined diversion pier in the large pumping station is analyzed [11]
The function and effect of flow field in improving flow pattern; Zhou Ji et al

The CFX software is applied to analyze the flow pattern in the forebay of the lateral inflow pump station, and
The rectification characteristics of Y type diversion pier, bottom sill and diversion wall are studied numerically. At present, the improvement of intake flow state of pumping station mainly focuses on the rectification measures in forebay and intake pond, while for urban rain water pump

Due to the restriction of pipeline layout, the station needs to adopt oblique pipe culvert inflow, which easily leads to poor flow pattern in the box culvert and uneven flow distribution in each hole. Due to the tight structural dimensions of the forebay and intake pond of the urban rainwater pumping station, the limited arrangement space of rectification measures, and the poor intake strips will significantly increase the difficulty of improving the flow pattern in the forebay and intake pond, which will not be conducive to the efficient and stable operation of the pumping station. Therefore, taking a typical city rainwater pumping station with oblique pipe culvert as an example, this paper uses CFD method to carry out in-depth analysis of hydraulic flow characteristics of box culvert, studies the existing bad flow patterns, proposes and analyzes the optimized rectification scheme, and then verifies it through physical model tests.

Calculation Model and Numerical Method

Figure 1 of 2.1 Geometrical Model and Calculation Area shows the plan and elevation layout of oblique pipe culvert inflow urban rainwater pumping station studied in this paper. The water intake system of the pumping station mainly includes: water intake main pipe, gate well, box culvert, forebay, water intake tank and water pump unit. The included angle between the water inlet main pipe and the center line of the box culvert of the pump station is 20°, and the box culvert uses 4 holes to flow in and faces the forebay of the pump station. The pump unit of the pump station adopts 6 submersible axial pumps with matching sizes, of which the design flow rate of 3# and 4# pumps located in the middle is 2.04 m^3/s, and the design of the remaining 4 pumps
The flow rate is 4.08 m^3/s, and the total design flow rate of the pump station is 20.4m^3/s. According to figure 1 , a three-dimensional etric model of the intake system of the pumping station is established, as shown in figure 2.

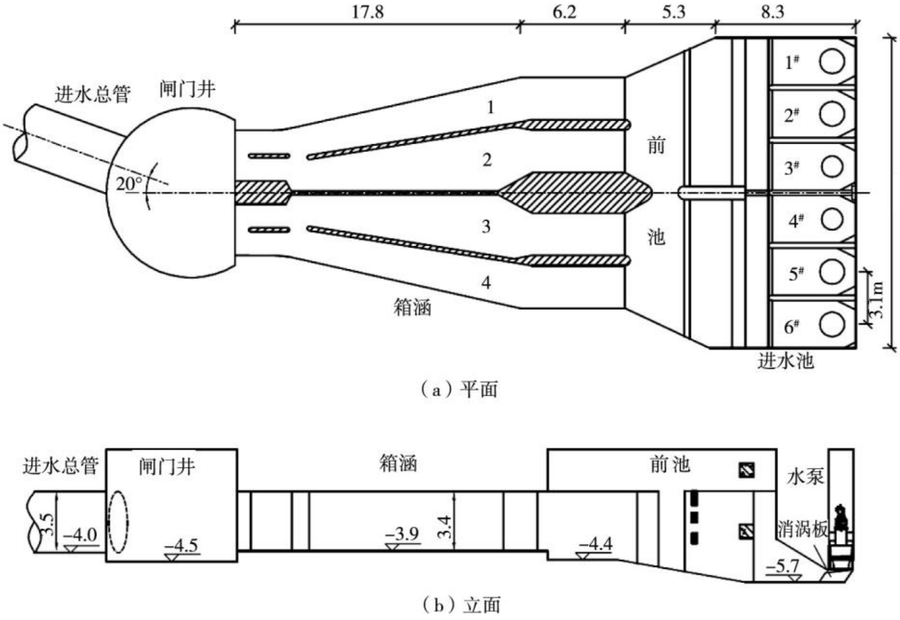


Figure 1 Layout of Plane and Facade of Urban Rainwater Pump Station (Unit: M)

The flow in 2.2 Control Equation and Turbulent Model pump station is usually in a turbulent state, and there are often some undesirable flow patterns such as swirling vortex, backflow and side wall shedding in the intake building of the pump station. Therefore, the numerical calculation in this paper is based on Reynolds Averaged Navier-Stokes Equations (RANS) and RNG (Re Normalization Group) and k-ε turbulence model to solve the three-dimensional incompressible turbulence *in* the pumping station. The finite volume method based on finite element is used to discretize the governing equations. The high-resolution scheme is used for the convection term, the central difference s cheme is used for the other terms, and the fully implicit multi-grid coupling method is used for solving the flow field.

2.3 Boundary Conditions and Computational Grids For boundary conditions, the inlet of the intake manifold of the pump station adopts the total pressure inlet boundary, the outlet of the pump station respectively gives its respective design flow rate, and the solid wall adopts the non-slip boundary condition. As the fluctuation of the water surface of the gate shaft and the forebay is small, in order to simplify the calculation, the free water surface is set as the symmetry plane based on the rigid cover assumption for processing. The application can automatically adjust to meet the calculation requirements of the scalable wall function. Treatment of near-wall flow. For pump station models with complex structures, unstructured grids with strong adaptability are used for calculation grids
See figure 3.
In order to reduce the influence of computational grid on numerical simulation results, grid convergence index method (GCI) based on Richardson extrapolation method is used.

The truncation error and calculation precision caused by the calculation grid are evaluated, and 3 grid schemes are respectively established: the number of grid cells in scheme 1 is 4 010 078 and the range of Y_+ is 11.7 ~ 983.6, The number of grid cells of scheme 2 is 1 781 084, y_+ is in the range of 18.6 ~ 1378.2, the number of grid cells of scheme 3 is 800 706 and y_+ is in the range of 28.3 ~ 2075.8, then grid scheme 1 is relative to scheme 2 and scheme 2 is relative to the grid of scheme 3
21 32
About 1.311 and 1.305 respectively. According to the GCI method, the hydraulic loss from the inlet manifold to the forebay inlet is selected.

Loss of *h* is the characteristic parameter. see table 1 for the parameters with body and fruit. among them, the calculated hydrodynamic loss of grid pattern 1~3 is calculated by numerical value.

H_1, H_2 and H_3 are 0.11, 0.108 and 0.102 m respectively. Obviously, they all change monotonously with the encryption of the grid, indicating that at present the grid

The numerical results on are monotonically convergent. At the same time, the extrapolation relative error *e* of hydraulic loss *h* And rel*a*tive error ea, respectively

It is 0.9% and 1.8%, and the grid convergence index value GCI $_f$ is 1.12%, which is less than 5%, indicating the grid dispersion error of dense grid (scheme 1)

It is smaller and has better calculation precision, and can be used as grid for numerical calculation.

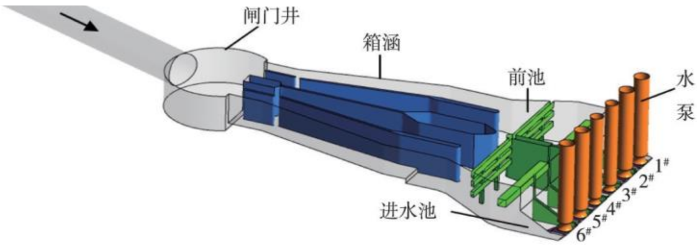
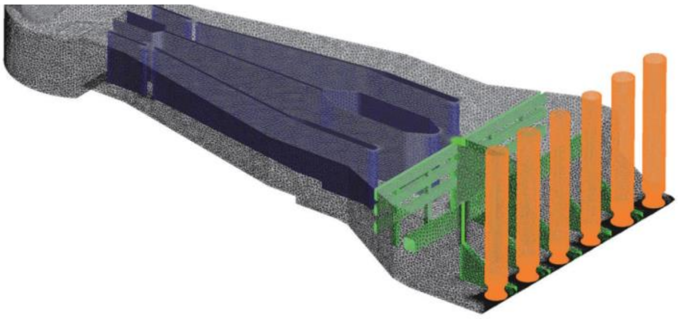


Figure 2 3D Geometric Model of Intake System of Urban Rainwater Pump Station



Graph 3 Computing Grid

Figure 4 shows the three-dimensional streamline diagram of the gate well, box culvert and forebay inlet area of the preliminary scheme of the pumping station. As can be seen from fig. 4 , the water flows obliquely into the gate shaft from the intake manifold. due to the sudden expansion of the round pipe into the gate shaft, the water flow entering the gate shaft cannot be fully diffused, which shows that the main flow is concentrated and large-scale vortex regions are formed on both sides. For oblique concentrated water flow, it is split to the left and right respectively after hitting the partition pier at the box culvert inlet: for the left water flow (viewed along the main flow direction), most water flow deflected to the left due to blocking by the partition pier in the box culvert enters the hole 2

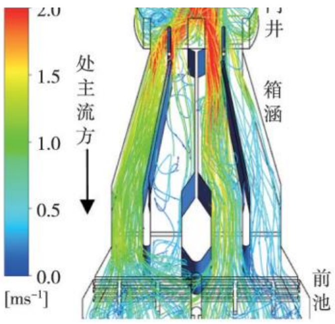
Inside, only a small amount of water can enter the hole 1 ; For the flow on the right side, the inflow from the gate shaft itself inclines to the right side, while the inflow from the partition pier in the box culvert

Blocking intensifies the degree of deflection to the right, allowing most of the water flow on the right to enter the hole 4 . Thus, oblique pipe culvert inflow

It is easy to cause uneven flow distribution in each hole of the box culvert of the pump station. Statistics show that the over-current flow of the box culvert holes 2 and 4 account for the total flow respectively.

42.52% and 38.41%, while the box culvert holes 1 and 3 account for 13.96% and 5.11% of the total flow respectively. In order to further understand the flow field characteristics at the gate shaft, box culvert and forebay inlet, a typical section as shown in figure 5 is selected for analysis, in which the horizontal section p is the middle section of the box culvert, and the vertical sections a, b, c and d are respectively the flow cross sections 0.5 m from the outlet of hole 4 of the box culvert.

Fig. 6 shows the velocity distribution nephogram and vector diagram on the horizontal section p. from the diagram, it can be clearly seen that the inflow in the gate shaft is oblique.



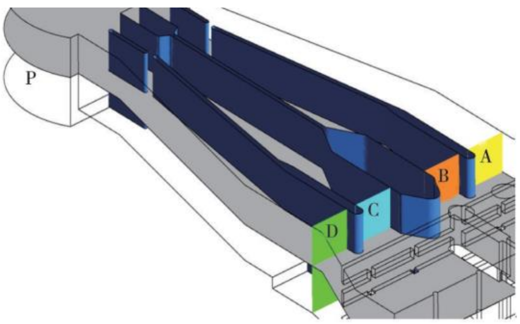


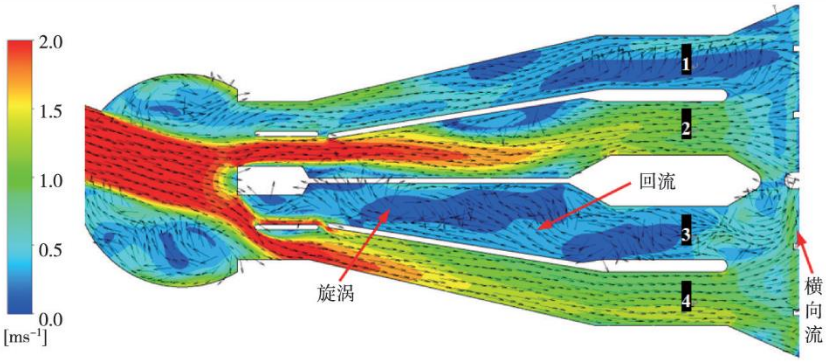
Figure 4 Three-dimensional Streamline Diagram of Preliminary Plan 5 Selected Typical Sections

The main flow is concentrated and there are vortex areas on both sides. The flow distribution in each hole of the box culvert is significantly different. In addition, it can also be seen from fig. 6 that the flow velocity in each hole of the box culvert is unevenly distributed, of which the flow velocity in hole 1 is relatively low and there is a certain bias flow at the end of the flow. in hole 2

The flow velocity is relatively high and there is a phenomenon of side wall shedding in the end region of the diffusion section of the box culvert hole, and there is obvious flow deviation in the hole 4 and the flow velocity along the flow direction to the right side.

The flow velocity in the hole 3 with the lowest flow distribution is obviously lower, and there are some undesirable flow patterns such as vortex and backflow. As shown in fig. 7

The velocity distribution nephogram along the main flow direction on the cross-section of the box culvert 4 near the ant difference in the velocity let of the forebay, thus causing



Map 6 Horizontal Section P Velocity

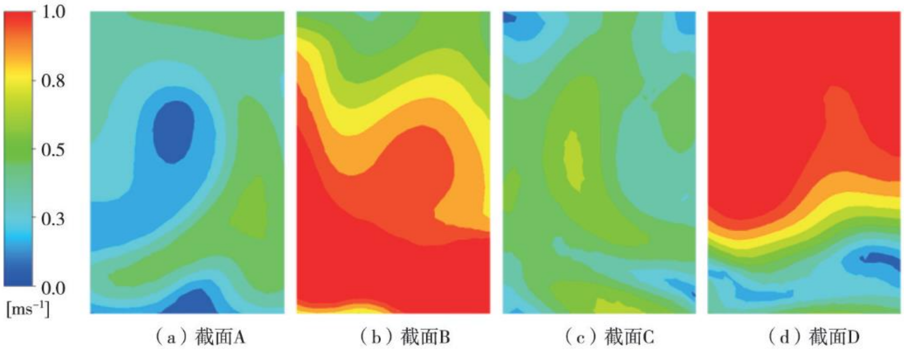


Figure 7 Box Culvert 4 Velocity Distribution Cloud Map of Hole Exit Section

Research on Rectification Measures for Inlet Water of 4 Box Culvert

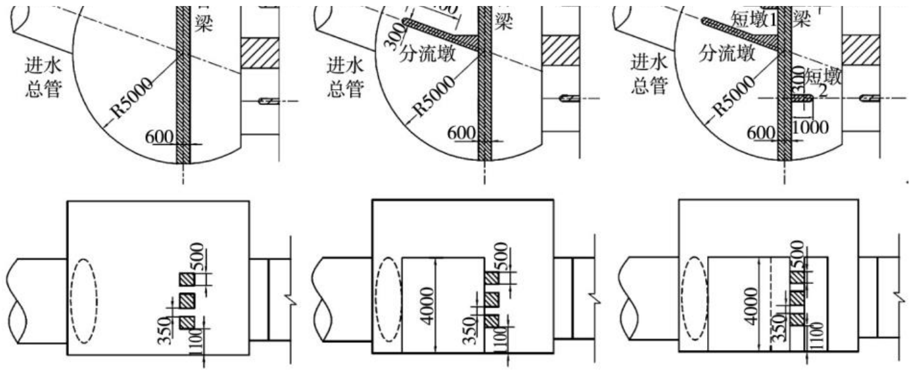
4.1 Scheme Design of Rectification Measures shows mainstream concentration due to the insufficient diffusion of oblique pipe culvert inflow in the gate well, which leads to uneven flow distribution in each hole of the box culvert and bad flow pattern in the gate well, box culvert and forebay. Therefore, it is proposed to homogenize the water flow by setting rectification measures in the gate shaft, so as to achieve the purpose of improving the uniformity of flow distribution in each hole of the box culvert and improving the flow pattern. As a new type of rectification measure, the composite beam has a simple structure and causes less hydraulic loss. It is often used to homogenize the inflow in the forebay of urban pumping stations. In this paper, composite beam measures are applied to gate shaft and its rectification effect is analyzed. At the same time, in order to obtain more ideal improvement effect, design

Two other combined rectification schemes combined with diversion piers are compared and analyzed. The structural layout of each rectification scheme is shown in Figure 8 . For rectification scheme 1, as shown in fig. 8 (a), it is composed of 3 crossbeams vertically arranged facing the box culvert and passing through the center of the gate shaft. For rectification scheme 2, refer to figure 8 (b), which is to add a diversion pier facing the center line of the intake manifold on the basis of scheme 1 ; And

Rectification scheme 3 is based on scheme 2. short diversion piers are arranged opposite to each other on both sides of the diversion pier. the specific structural dimensions are shown in figure 8 (c).

Figure 9 shows the three-dimensional geometric model of the above-mentioned 3 rectification schemes, which will be compared and analyzed based on CFD numerical simulation method

Improvement effect of 3 rectification measures.



Structural Arrangement of Figure 8 3 Rectification Schemes Designed in Gate Shaft (Unit: mm ）

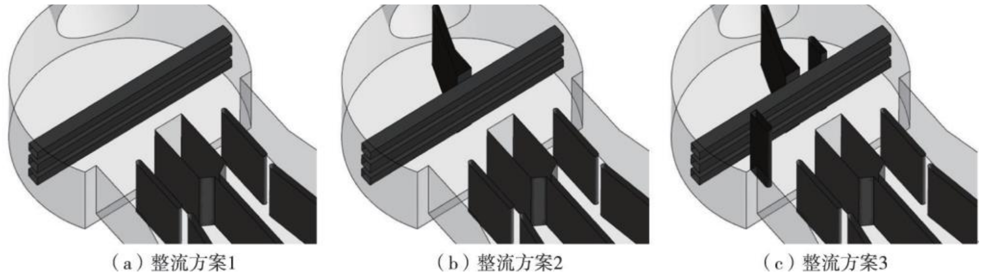


Figure 9 3D Geometric Model of Three Rectification Measures in Gate Shaft of Pumping Station

The rectification effect analysis of 4.2 adopts the above 3 rectification schemes respectively. The inlet flow states at the gate shaft, box culvert and forebay inlet of the pump station are as follows

As shown in fig. 10 , compared with the preliminary scheme (see fig. 4 and fig. 6), the rectification effect of each rectification scheme on the inlet flow state of the pump station is obviously different. For rectification scheme 1, refer to Figure 10 (A), the composite beam has a certain homogenization effect on the oblique inflow of gate shaft, but the flow entering the box culvert still has uneven flow distribution, in which the flow distribution of the side holes on both sides of the box culvert is more, accounting for 35.39% (hole 1) and 40.04% (hole 4) of the total flow respectively, while the flow distribution of the middle two holes is lower, accounting for 11.25% (hole 2) and 13.32% (hole 3) of the total flow respectively. In addition, there is still an obvious flow deviation phenomenon in hole 4 , and adverse flow patterns such as backflow and vortex exist in holes 2 and 3 with low flow distribution.

At the same time, there is still obvious lateral flow at the inlet of the forebay of the pump station. For rectification scheme 2, refer to figure 10 (b), the diagonal inflow entering the gate shaft is diverted first by adding a diversion pier facing the center of the intake manifold in front of the combined beam. Among them, for the right water flow

(Looking along the flow direction), the flow will continue in the original direction. For the left-hand flow, the left-hand side wall of the diversion pier has a bent structure, which changes the left-hand flow from oblique to forward flow. Both flows are homogenized when passing through the composite beam, and the flows of holes 1—4 respectively account for

The 33.92%, 15.44%, 14.44% and 36.21% of the total flow have slightly increased the flow distribution homogenization degree of each hole of the box culvert compared with the rectification scheme 1, but there is still a bad flow pattern in the box culvert and at its outlet, and the flow distribution uniformity and velocity distribution of the box culvert still need to be further improved. For the rectification scheme 3, as shown in fig. 10 (c), on the basis of the rectification scheme 2 , short diversion piers are arranged on both sides of the diversion pier and on the back of the front and back of the composite beam to further homogenize and guide the diversion on both sides of the diversion pier. compared with the preliminary scheme and the other two rectification schemes, Not only does the flow distribution in each hole of the box culvert become more uniform, so that the flow distribution in the holes 1—4 accounts for 23.96%, 25.49%, 22.48% and 28.07% of the total flow, but also the flow pattern in each hole of the box culvert and at the inlet of the forebay has been significantly improved.

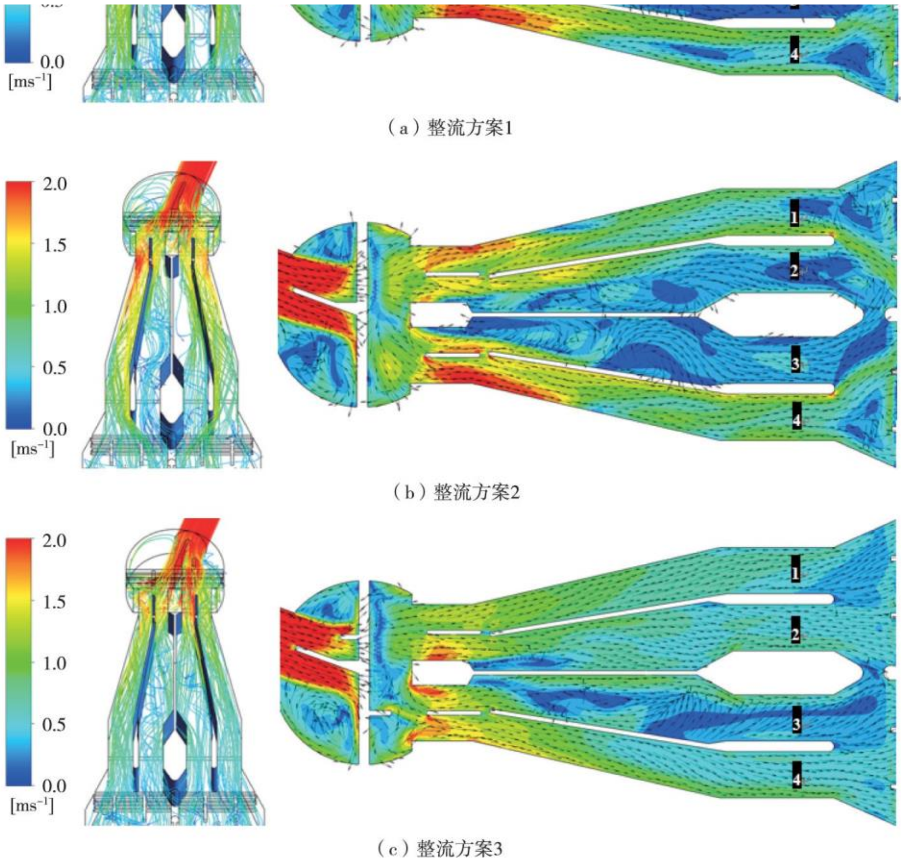


Figure 10 Inlet Flow State of Each Rectification Scheme

Figure 11 shows the velocity distribution nephogram along the main flow direction at the A, B, C and D sections of the outlets of the box culvert 4 of each rectification scheme. From the figure, it can be found that compared with other schemes, the rectification scheme 3 effectively improves the uniformity of the outlet velocity of each hole of the box culvert.

4.3 Analysis on Flow Distribution Characteristics of Box Culvert In order to better evaluate the improvement effect of 3 rectification schemes on flow distribution characteristics of box culverts in pumping stations, the following two parameters are *compared and analyzed: flow distribution imbalance* E_I and total flow distribution uniformity S, where E_I and S are respectively defined as:

Where: q_I is the flow rate of water in the I hole, m^3/s; Q_a is the average flow rate of each hole in the box culvert, m^3/s; n is the number of culvert holes, i.e. n =4.

Fig. 12 shows the distribution of e_I value of flow distribution imbalance in each *hole of box culvert in the preliminary scheme and 3 rectification schemes, where* e_I

The closer the value is to 0 , the more uniform the flow distribution of the hole is. As can be seen from fig. 12 , the box culvert flow distribution in the preliminary scheme does not

Both phenomena are relatively serious. The flow distribution of holes 2 and 4 is obviously larger, reaching 0.175 and 0.134 respectively, while the flow distribution of holes 1 and 3 is lower, reaching -0.11 and -0.199 respectively. By installing rectification measures in the gate shaft, the uniformity of flow distribution in the box culvert can be improved. Among them, rectification schemes 1 and 2 have not achieved significant improvement, while rectification scheme 3 can effectively improve the flow distribution of each hole in the box culvert.

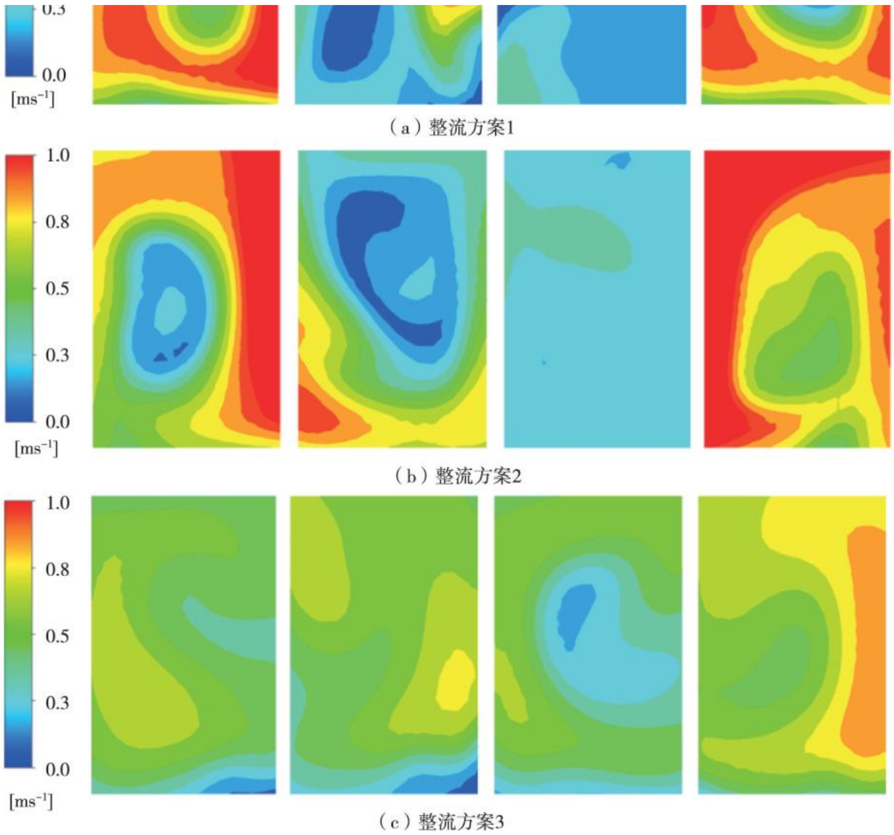


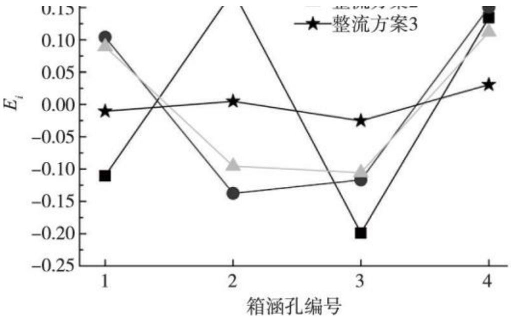
Figure 11 Box Culvert of Each Rectification Scheme 4 Velocity Distribution Cloud Map of Hole Exit Section

The uniformity of the degree, make each hole e_I value reduced to between ±0.03 .

The total flow distribution uniformity *s* of box culverts before and after rectification is shown in figure 13 , wherein the value of the total flow distribution uniformity *s* is closer to

1 indicates that the more uniform the flow distribution in each hole of the box culvert. It can be clearly seen from fig. 13 that the overall flow distribution uniformity *s* of the box culvert is obviously low, only 0.268 ; , without the preliminary scheme of rectification measures. However, the flow distribution uniformity of each hole in the box culvert can be improved by arranging rectification measures in the gate shaft, and the rectification scheme 3 has the most significant improvement, which can increase the total flow distribution uniformity *S* value to 0.905. Therefore, the rectification scheme 3 can be set in the gate shaft to improve the flow distribution characteristics of the box culvert of the rainwater pumping station in the city.

4.4 Verification and Analysis of Physical Model To further verify the improvement effect of rectification scheme 3 , rectification is compared and analyzed based on physical model tests.



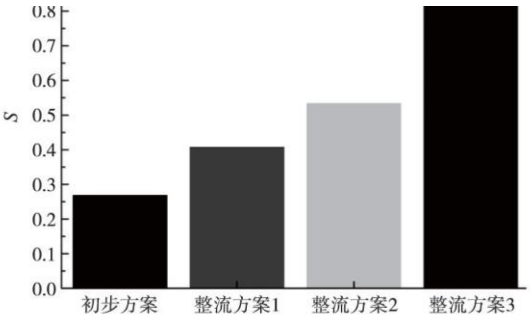


Diagram 12 Flow Distribution Unbalance Value Diagram of Each Hole in Box Culvert 13 Comparison of Total Flow Distribution Uniformity of Each Scheme

Velocity distribution of typical sections at the outlet of front and rear box culverts and the inlet of water intake tank. The physical model is designed according to the gravity similarity criterion. considering the requirements of the model water flow in the resistance square area and the selection of the model pump, the linear scale λ and l of the model are determined to be 8. the physical photos of the physical model are shown in fig. 14 . Fig. 15 shows the arrangement of typical sections and measuring points in the physical model, in which section a is located 62.5 mm from the outlet of the box culvert in the box culvert hole, section b is located 75 mm from the inlet of the water intake tank, 3 measuring vertical lines are arranged in each hole of the box culvert and in front of the inlet of the water intake tank of the water pump in the horizontal direction, and each vertical line is uniformly distributed with 9 vertical measuring points from the near water bottom to the near water surface. The ADV (acoustic Doppler velocimeter) is used to measure the velocity of each measuring point. through statistical averaging and similar conversion of the velocity components of each measuring point along the main flow direction of the forebay on each measuring vertical line, the vertical average velocity distribution diagram of each typical section measuring point before and after rectification is obtained, as shown in fig. 16. Fig. 17 is a comparison chart of the flow distribution coefficient of each hole of the box culvert (the percentage of each hole flow to the total flow) obtained by numerical calculation and experimental measurement statistics before and after rectification.

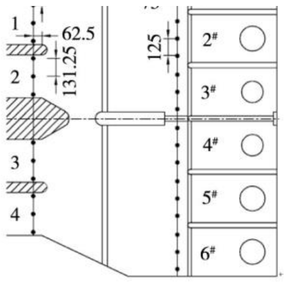
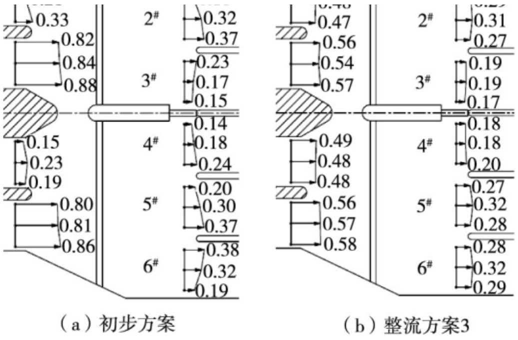


Figure 14 Physical Model Photo (Rectification Scheme 3) Figure 15 Typical Section and Survey Point Arrangement (Unit: mm)

According to figures 16 and 17 , it can be found that the outlet velocity distribution of box culvert in the preliminary scheme of pumping station is uneven and the flow distribution is obviously different, among which

The flow distribution of box culvert hole 2 and hole 4 is relatively large and the flow velocity is relatively high, while the flow distribution of hole 1 and hole 3 is relatively small and the flow velocity is relatively low. At the same time, the uneven flow velocity distribution at the outlet of the box culvert directly affects the inlet flow state of the forebay, resulting in uneven flow velocity distribution before the inlet of the cistern. By installing rectification scheme 3 in the gate shaft, the flow distribution characteristics of each hole of the box culvert and the uniformity of the flow velocity distribution at the outlet of each hole of the box culvert and before the inlet of the water tank are significantly improved. Figure 18 shows the physical model test and numerical simulation of the rectification scheme 3 before the outlet of the box culvert and the inlet of the water tank.

Calculated and statistically obtained the velocity distribution comparison chart of typical section measuring points along the mainstream direction. From figure 17 and figure 18 , it can be seen that the results of physical model test and numerical simulation calculation are in good agreement, which verifies the reliability of the numerical simulation method in this paper, both from the distribution law of flow distribution coefficient in each hole of box culvert and the distribution law of flow velocity at measuring points of typical section.



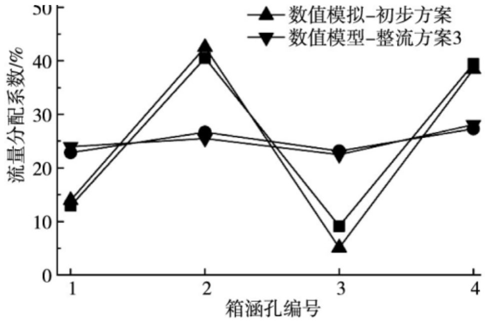


Figure 16 Vertical Average Velocity Distribution of Typical Section Survey Points (Unit: M/S) Figure 17 Comparison of Flow Distribution Coefficient of Box Culvert Holes

5 Conclusion

According to a city rainwater pump station with oblique pipe culvert inflow, the analysis of box culvert inflow flow state and its rectification measures were carried out, and the following main conclusions were obtained: (1) due to the influence of inertial force, the oblique pipe culvert inflow did not fully diffuse in the gate shaft, and the main flow was concentrated and large-scale vortex areas were formed on both sides; Oblique inflow tends to lead to uneven flow distribution in each hole of the box culvert, resulting in generation in the box culvert hole.

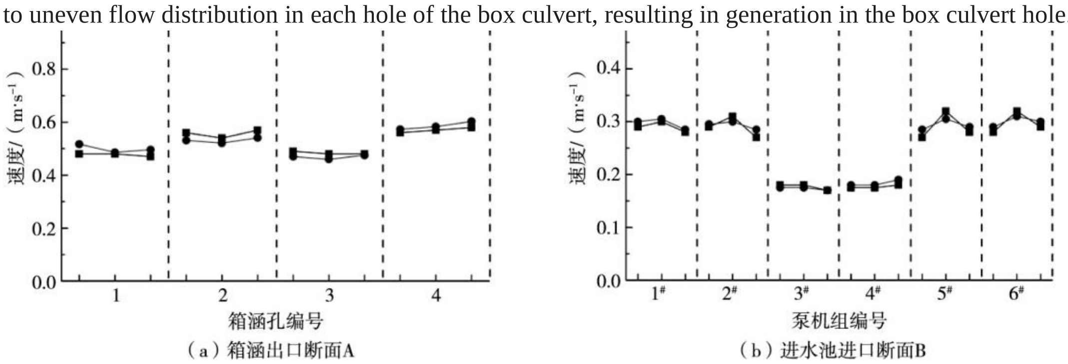


Figure 18 Rectification Scheme 3 Comparison of Velocity Points of Each Measuring Vertical Line in Mainstream Direction

Unfavorable hydraulic phenomena such as partial flow, backflow, vortex, etc. worsen the intake flow state of the forebay and intake pool, which is not conducive to the safe operation of the pump station. (2) gate

The combined measures of "diversion piers, composite beams and short diversion piers arranged opposite to each other" in the well have the most significant rectifying effect on oblique inflow. The diversion pier effectively diverts the oblique inflow of the gate shaft at first. One side of the water flow is diverted by the diversion pier into the forward inflow, and then becomes more uniform by the homogenization of the composite beam and the diversion of the rear short diversion pier. The other side of the water flow continues to flow along the oblique direction, and is effectively homogenized by the diversion and diversion of the front short diversion pier and the homogenization of the composite beam, thus finally improving the flow pattern at the gate shaft, box culvert and forebay inlet and increasing the uniformity of flow distribution in each hole of the box culvert. (3) The results of physical model tests are in good agreement with the numerical simulation results, which further verifies the effectiveness of rectification measures and the reliability of numerical simulation methods.

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