

Article

Study on the Mechanism and Control Measures of Sediment Deposition in the Forebay of a Forward Pumping Station

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Abstract

To address the problems of disordered flow patterns, wall-separated recirculation, and sediment deposition that commonly occur in the forebay of forward-facing pumping stations on sediment-laden rivers, the first-stage Xin Zhuangji Pumping Station in Ningxia was selected as the study case. A three-dimensional numerical simulation was conducted using the Realizable $k-\varepsilon$ turbulence model coupled with the Mixture two-phase flow model for water–sediment flow. The regulation effects of splayed guide walls with different guide-wall deflection angles on the velocity distribution, vortex structures, and sediment deposition in the forebay were investigated. The results show that large-scale recirculation zones exist on both sides of the prototype forebay, accompanied by uneven velocity distribution and severe sediment deposition within the recirculation regions. The installation of splayed guide walls can effectively suppress lateral recirculation, expand the mainstream flow region, and reduce the deposition area. However, the regulation effect of the diffusion-type guide wall varied significantly with the guide-wall deflection angle. Since the main objective of this study was to control sediment deposition rather than to maximize a single hydraulic indicator, a multi-criteria screening method oriented toward sediment-reduction control was adopted. Under the ($\theta = 25^\circ$) scheme, the reduction ratio of the overall potential deposition area based on the primary threshold criterion reached the maximum value of 53.67%, the recirculation area on plane Z1 decreased by 23.23%, the global recirculation coefficient increased to 68.69%, and the sediment deposition efficiency decreased to 0.033. The axial velocity uniformities at the suction-pipe sections of pumps B# and C# were 71.23% and 80.61%, respectively. Although the ($\theta = 30^\circ$) scheme produced the highest velocity uniformity for pump B# and showed a slightly better reduction effect on local high-concentration sediment-enrichment regions, the ($\theta = 25^\circ$) scheme exhibited a more balanced improvement in overall sediment-deposition control and flow-pattern regulation. Therefore, under the investigated operating condition, the ($\theta = 25^\circ$) scheme is recommended as the guide-wall deflection angle oriented toward sediment-reduction control.

Keywords: pumping station; forward-facing forebay; two-phase flow; numerical simulation; splayed guide wall

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1. Introduction

With the rapid development of the social economy and the increasingly prominent conflict between the temporal and spatial distribution of regional water resources, higher requirements have been imposed on the operational safety, stability, and energy efficiency of pumping stations in projects such as inter-basin water transfer, agricultural irrigation, urban water supply and drainage, and flood control and drainage. As a key hydraulic structure in water-resource conveyance and distribution systems, a pumping station is strongly affected by its intake flow conditions, which directly influence the hydraulic performance of the pump system, unit vibration, energy consumption, and service life. As an important transitional water body connecting the diversion channel with the intake basin and pump chamber, the forebay serves to diffuse the incoming flow, homogenize the velocity distribution, and improve the intake conditions for each pump unit. When the planar diffusion angle, bed slope, unit arrangement, operating combination, or sediment-laden inflow conditions are unreasonable, undesirable flow patterns, such as biased flow, recirculation, wall-separated flow, large-scale vortices, and low-velocity stagnant zones, are prone to form in the forebay. These phenomena may further lead to uneven velocity distribution at the pump intake, enhanced intake vortex belts, reduced pump-unit efficiency, and even cavitation, abrasion, and structural vibration [1,2].

To address these issues, numerous scholars have conducted extensive research. In the field of flow-rectification measures, Zheng et al. [3] calculated the flow patterns in the forebay before and after rectification under different start-up schemes by adopting two rectification measures: a single bottom sill and a combined bottom sill–guide pier arrangement. The results showed that, before flow rectification, large-scale undesirable flow structures, such as recirculation and vortices, existed in the forebay, accompanied by an uneven velocity distribution. Adding a bottom sill in the forebay divided the flow and caused it to diffuse toward both sides. The combined rectification facility consisting of a bottom sill and guide piers was beneficial for dispersing the incoming flow and making the discharge distribution among the pump units more uniform. As a result, recirculation and vortices in the forebay were largely eliminated, and the flow pattern was significantly improved. Luo et al. [4] investigated a laterally asymmetric forebay and arranged a straight guide pier combined with curved wing walls and a straight guide pier combined with curved wing walls and a V-shaped guide pier to eliminate biased flow and large-scale vortices in the forebay. Wang et al. [5] investigated the forebay of a lateral-flow pumping station and proposed a trapezoidal-array partition scheme for lateral-flow forebays. By adjusting the partition positions and rotating the partition angles, the flow pattern was optimized. The results showed that the vortex area was reduced, the velocity uniformity was improved, and the thickness of sediment deposition decreased. Feng et al. [6] combined physical model tests with numerical simulations to compare the effects of guide piers arranged at different positions on the flow pattern in the forebay. They further optimized the rectification scheme using the response surface methodology. The results showed that, compared with the case without guide piers, the velocity distribution uniformity and global recirculation coefficient of the final optimized scheme increased by 28.02% and 13.72%, respectively. Xu et al. [7] investigated the rectification effect of splayed guide piers. The results showed that arranging splayed guide piers in the forebay could effectively eliminate the large-scale recirculation zones on both sides of the forebay. After two groups of splayed guide piers were arranged along the direction of the flow-channel dividing piers, the recirculation zones in the planar flow field disappeared, the axial velocity distribution uniformity of the side pump units was improved compared with that of the original scheme, and the velocity distribution at the pump intakes became more uniform. Song et al. [8] investigated a lateral-intake pumping station and compared several rectification measures, including Y-shaped guide piers, bottom sills, and columns.

They indicated that the reasonable arrangement of rectification structures could weaken biased flow, recirculation, and vortices in the forebay, thereby improving the uniformity of the velocity distribution in the intake basin. Yang et al. [9] combined numerical simulations with physical model tests to investigate the flow pattern and anti-vortex measures in the forebay of a multi-unit pumping station. The results showed that arranging anti-vortex facilities in regions with undesirable flow patterns could effectively improve the intake conditions of each pump unit. Nasr et al. [10] proposed a combined rectification measure consisting of parabolic walls and guide piers for the forebay of a multi-unit pumping station with lateral inflow. The results showed that this combined rectification approach could significantly reduce the vortex area and improve the velocity uniformity. Wang et al. [11] combined the particle swarm optimization algorithm with a Gaussian process model to optimize the parameters of a hollow rectifying sill in the forebay, providing a new approach for the parametric design of flow-rectification facilities. Zhang et al. [12] investigated the layout parameters of guide piers in the forebay of a lateral-intake pumping station based on the orthogonal experimental method. They found that factors such as the position, length, and angle of the guide piers had significant effects on flow-pattern improvement. Xu et al. [13] proposed a contraction-type guide pier as a flow-rectification measure and verified its effectiveness in improving the flow pattern of an asymmetric forebay through numerical simulations and experiments. Luo et al. [14] analyzed the vortex-suppression mechanism of bottom sills in the forebay of a lateral-flow pumping station from the perspectives of vortex energy and entropy production. They pointed out that bottom sills could reduce the intensity of rolling vortices in the forebay and improve the velocity uniformity at the intake section. Ye et al. [15] reviewed advances in hydrodynamic research on pumping station systems and pointed out that optimization of forebay flow patterns and the design of flow-rectification measures remain important directions for improving the operational efficiency and stability of pumping stations. Ji et al. [16] investigated the intake characteristics of a pumping station with a 90° lateral inflow arrangement, providing a reference for optimizing forebay flow patterns under complex intake conditions.

However, existing studies on frontal-intake pumping-station forebays still have several limitations. First, most previous studies have mainly focused on clear-water flow or single-phase hydraulic optimization, whereas the coupled interaction between recirculation structures and suspended-sediment transport in sediment-laden forebays remains insufficiently investigated. Second, although guide piers and guide walls have been widely used as engineering measures for flow rectification, quantitative studies on the effects of guide-wall deflection angle on vortex suppression and sediment-retention characteristics are still limited. Therefore, the main innovation of this study lies not only in the practical application of splayed guide walls as an engineering measure, but also in the comprehensive evaluation of their hydraulic regulation effect and sediment-control performance based on a real sediment-laden pumping-station forebay project.

In this study, the Xin Zhuangji first-stage Pumping Station in Hong Sibü, Ningxia, was selected as the engineering case. Field measurements of the flow velocity in the pumping-station forebay were conducted using an acoustic Doppler current profiler (ADCP). The instrument can measure underwater flow velocities within a measurement range of 0.2–80 m, with a resolution of 0.001 m and an accuracy of 1%. Based on the field-measured data, a three-dimensional numerical model of water–sediment two-phase flow was established. Guide-wall deflection-angle optimization was then carried out with sediment deposition prevention and control as the primary objective, while the hydraulic performance at the intakes of the operating pumps was considered as a necessary constraint. By setting multiple guide-wall optimization schemes with different inclination angles, the effects of guide-wall inclination angle on the planar flow field, near-bed recircu-

lation zone, flow-velocity uniformity at the pump intakes, sediment volume-fraction distribution, and sediment deposition efficiency were comparatively analyzed. On this basis, a multi-criteria screening framework oriented toward sediment-reduction control was adopted to determine the recommended guide-wall deflection angle, thereby avoiding selection based simply on the optimum value of a single hydraulic indicator. The results can provide a technical reference for hydraulic optimization and sediment deposition prevention in frontal-intake pumping-station forebays under sediment-laden water diversion conditions.

2. Engineering Background

2.1. Project Overview

The first-stage Xin Zhuangji Pumping Station in Ningxia diverts water from the Yellow River, where the flow has a high sediment concentration, with a multi-year average sediment concentration of 2.88 kg/m^3 . The first-stage Xin Zhuangji Pumping Station controls an irrigated area of 160.53 km^2 and has a design discharge of $6.22 \text{ m}^3/\text{s}$. The maximum forebay water level, design water level, and minimum operating water level are 1345.88 m, 1345.72 m, and 1344.47 m, respectively. The pumping-station project consists of a diversion channel, a forebay, and an intake basin. The forebay is a sloping section with a slope i of 1:4. The forebay length L is 11 m, with an inlet width of 3 m, a downstream-end width of 21 m, and a side-wall diffusion angle α of 40° . The intake basin is 6 m long. The pumping station was equipped with three pump units, designated as A#, B#, and C#. Under the design operating condition, pump units B# and C# were in operation. The diameter of the pump suction pipe was 1.2 m, as shown in Figure 1.

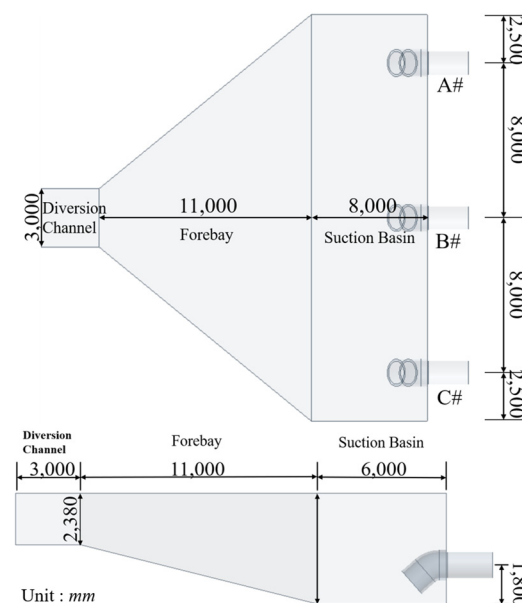


Figure 1. Structural diagram of the forebay of a forward pumping station.

2.2. Field Investigation

In August 2025, the project team conducted field measurements and sampling analysis at the site. The average velocity at the forebay inlet was 0.69 m/s. The measured flow-field pattern indicated flow separation along the side walls of the pumping-station forebay, and large-scale recirculating vortices were observed in the regions on both sides of the intake basin. The sediment particle-size distribution was measured using a Bettersize 2000 laser particle-size analyzer. The measured sediment particle-size range was $0.29\text{--}131.5 \text{ }\mu\text{m}$, with a median particle size of $15 \text{ }\mu\text{m}$. The particle-size analysis results showed that fine

particles smaller than 66.87 μm accounted for 95.83% of the total sediment, indicating that the suspended sediment in the forebay was dominated by fine particles. As shown in Table 1. Therefore, the median particle size of 0.015 mm was selected as the representative sediment particle size in the numerical simulations. The main objective of this study was to compare the relative hydraulic performance and sediment-reduction effects of different guide-wall layout schemes under the same inflow sediment concentration, rather than to predict the absolute amount of sediment deposition. Therefore, the same representative sediment particle size was adopted for all simulated cases to ensure a consistent basis for comparison among different schemes. The water–sediment two-phase flow was simulated using the Mixture model, in which the water phase was treated as the primary phase and the sediment phase as the secondary phase. The interaction between the two phases was considered through the mixture continuity and momentum equations, reflecting the two-way coupling characteristics of the water–sediment two-phase flow. The relative motion between the water and sediment phases was described using the algebraic slip formulation in the Mixture model. Sediment settling was governed by the balance among gravity, buoyancy, and interphase drag, whereas sediment diffusion was controlled by turbulent diffusion. It should be noted that the use of a single representative particle size may affect the prediction accuracy of the absolute amount of sediment deposition, because the sediment settling velocity is closely related to particle size. However, since all guide-wall schemes were evaluated using the same sediment physical parameters, this simplification does not affect the comparison of the relative sediment-reduction effects among different guide-wall layout schemes. Future studies will consider multiple particle-size fractions to further improve the accuracy of graded sediment transport and deposition prediction.

Table 1. Sediment particle-size distribution characteristics at the forebay inlet.

Particle-Size Range μm	Sediment Concentration %	Cumulative Content %	Particle-Size Range μm	Sediment Concentration %	Cumulative Content %
0.299–1.156	4.47	4.47	8.794–17.29	19.47	56.58
1.156–2.274	6.17	10.64	17.29–34.00	22.87	79.45
2.274–4.472	11.03	21.67	34.00–66.87	16.38	95.83
4.472–8.794	15.44	37.11	66.87–131.5	4.17	100

3. Numerical Model Construction and Validation

3.1. Model Establishment and Boundary Conditions

In the pumping-station forebay, both a liquid phase and a solid phase consisting of suspended sediment particles are present. Therefore, the flow-field structure in the forebay can be treated as an incompressible water–sediment two-phase flow. Considering that heat exchange between the water and sediment phases is negligible, the influence of energy transfer on the flow characteristics can be ignored. Therefore, the energy equation was not considered in the model, and the focus was mainly placed on the coupling of mass and momentum between the water and sediment phases. For forebays with high sediment concentrations, the settling and deposition of suspended sediment continuously alter the bed morphology of the forebay, thereby further deteriorating the flow-field structure. In this study, the Mixture two-phase flow model [17] was employed to accurately characterize the water–sediment flow dynamics in the forebay. By coupling the continuity equation, momentum equation, and volume-fraction equations for the water and sediment phases, the model can efficiently capture the sediment transport characteristics. For the complex turbulent phenomena that readily occur in forward-facing intake forebays, such as flow

separation and secondary flow, the Realizable k - ε turbulence model [18] was selected. This model incorporates corrections for flow rotation and curvature effects, thereby improving the calculation methods for the turbulent eddy viscosity and dissipation rate. The governing equations describing the water–sediment motion in the pumping-station forebay are given as follows [19]:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{v}_m) = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\rho_m \mathbf{v}_m) + \nabla \cdot (\rho_m \mathbf{v}_m \mathbf{v}_m) = & -\nabla p + \nabla \cdot \left[\mu_m (\nabla \mathbf{v}_m + \nabla \mathbf{v}_m^T) \right] \\ & + \rho_m \mathbf{g} + \mathbf{F} - \nabla \cdot \left(\sum_{k=1}^n \alpha_k \rho_k \mathbf{v}_{dr,k} \mathbf{v}_{dr,k} \right) \end{aligned} \quad (2)$$

where ρ_m denotes the mixture density, ρ_k denotes the density of phase k , α_k denotes the volume fraction of phase k , $\mathbf{v}_m$ denotes the mean velocity of the mixture, p denotes the hydrostatic pressure, n denotes the number of phases, μ_m denotes the dynamic viscosity of the mixture, $\mathbf{g}$ denotes the gravitational acceleration, $\mathbf{F}$ denotes the body force, $\mathbf{v}_{dr,k}$ denotes the drift velocity of the secondary phase k , and t denotes time.

Based on the field-measured data, the diversion channel was specified as the inlet boundary of the computational model, where a velocity-inlet condition was applied with an inlet velocity of 0.69 m/s. The pump suction pipes were specified as the outlet boundaries, where pressure-outlet conditions were applied and controlled by the standard atmospheric pressure. The free surface was treated using the rigid-lid assumption because the Froude number of the forebay flow under the investigated operating condition was low and the free-surface deformation was weak. The measured inlet velocity was 0.69 m/s, corresponding to a dynamic head of approximately 0.024 m, which was small relative to the operating water depth. In addition, no obvious wave breaking, hydraulic jump, or strong free-surface fluctuation was observed during the field investigation. Although the longitudinal bed slope ratio of the forebay was 1:4, this slope was explicitly included in the computational geometry. The rigid-lid assumption only indicates that the water-surface elevation remained essentially unchanged during the simulation and did not simplify the inclined-bed geometry. Since this study mainly focused on near-bed recirculation, sediment-enrichment regions, and flow distribution at the pump intakes, this assumption was considered appropriate for engineering-scale numerical simulations under the investigated operating condition. The sidewalls and bottom of the forebay were set as no-slip walls and treated using the standard wall-function method [20], with a wall roughness of 0.1 mm. Because relatively strong near-wall shear occurs in the diffusion section of the forebay and near the sidewalls, the standard wall-function method can reasonably resolve the near-wall flow while balancing computational accuracy and efficiency. During the calculation, the wall (y^+) value was maintained at approximately 43, indicating that the near-wall grid cells were located within the logarithmic-law region. Therefore, the use of standard wall functions was appropriate. The convergence tolerance of the iterative residuals was controlled below 10^{-4} [21].

The numerical simulations were performed using ANSYS Fluent 2024R2. The SIMPLEC algorithm was adopted for pressure–velocity coupling, and the discretization scheme was set to second-order upwind. Standard wall functions were applied, and transient simulations were conducted. The convergence criteria were defined as follows: the residuals of all governing equations remained stably below 10^{-4} without continuous increase, the mass-flow imbalance between the inlet and outlet was less than 0.5%, the total simulation time was 1000 s, and the time step was 0.01 s.

Based on sampling in the forebay and measurements conducted using a laser particle-size analyzer, the median sediment particle size was determined to be 15 μm . In the water–sediment two-phase flow model, water was defined as the primary phase, with a density of 998.2 kg/m^3 . Sediment was defined as the secondary phase, and its density was set to 2500 kg/m^3 based on the physical properties of natural sediment. Based on the measured data, the sediment volume fraction of the inflow entering the forebay was set to 0.1%, and the sediment phase was numerically simulated as uniform sand with a median particle size of 0.015 mm.

The numerical simulations in this study were conducted under fixed-bed conditions, without considering bed deformation or morphological evolution. Therefore, sediment deposition was not directly simulated through changes in bed elevation. Instead, the sediment transport characteristics were evaluated based on the spatial distribution of sediment volume fraction and the corresponding high-sediment-concentration regions, which represent sediment retention and potential deposition risk within the forebay. Thus, the “sediment deposition” described in this study refers to the potential deposition tendency inferred from the simulated flow field and sediment concentration field, rather than the actual process of geomorphic deposition.

3.2. Mesh Generation and Model Validation

The computational domain of the pumping-station forebay system consists of the diversion channel, forebay, intake basin, and pump suction pipes. Owing to its relatively complex geometry, the forebay geometric model was discretized using hexahedral meshes generated with ANSYS Meshing 2024R2. Hexahedral meshes provide a more uniform distribution of degrees of freedom within each cell and higher solution accuracy, making them particularly suitable for the calculation of field variables such as stress and flow. Under the same accuracy requirement, fewer mesh elements are needed, resulting in higher computational efficiency and lower memory consumption. In addition, mesh density directly affects the accuracy and solution efficiency of the simulation. Insufficient mesh density may lead to numerical oscillations in the simulation results, whereas an excessively dense mesh significantly increases the computational time. Therefore, mesh refinement was applied near the guide walls and at the outlet of the forebay, and hydraulic loss was selected as the key evaluation indicator for mesh-independence verification, as expressed in Equation (3). Three mesh schemes with different numbers of cells were established, containing 1.1297 million, 1.20 million, and 2.113 million cells, respectively. The corresponding hydraulic losses of the three mesh schemes were 0.25 m, 0.21 m, and 0.20 m, respectively. Comparative calculations using a series of meshes with different densities showed that when the total number of cells reached or exceeded 1.20 million, with a maximum mesh size of 0.1 m, a minimum mesh size of 0.004 m, and a mesh quality greater than 0.3, the calculated hydraulic loss tended to converge. In addition, the differences in the recirculation area on plane Z1 and the peak sediment volume fraction between the 1.20 million-cell mesh and the finer 2.113 million-cell mesh were very small. The recirculation areas on plane Z1 were 106.62 m^2 and 107.47 m^2 , respectively, and the peak sediment volume fraction remained 0.014 for both meshes. This indicates that the predicted near-bed recirculation field and sediment distribution were essentially independent of the mesh number.

Therefore, the selected mesh satisfies the mesh-independence criterion and provides sufficient accuracy for the present engineering-scale numerical simulations.

$$H_f = \frac{(p_{in} - p_{out})}{\rho g} \quad (3)$$

where Hf is the hydraulic loss based on mass-averaged total pressure, m; p_{in} is the inlet total pressure, Pa; and p_{out} is the outlet total pressure, Pa.

To facilitate the quantitative analysis of the flow-field characteristics in the forebay, two transverse sections, X1 and X2, were arranged in the lateral direction, and five longitudinal sections, Y1, Y2, Y3, Y4, and Y5, were arranged in the streamwise direction; along the water-depth direction, two horizontal planes, Z1 and Z2, were arranged. The section arrangement is shown in Figure 2b, and the specific parameters are listed in Table 2.

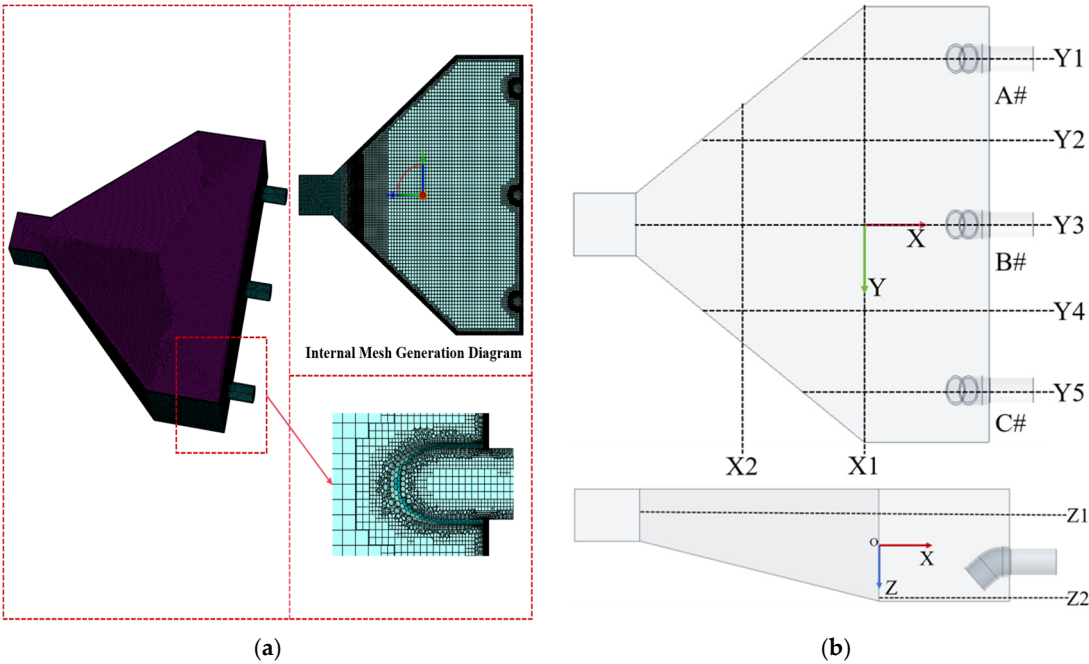


Figure 2. Mesh and observation cross-section layout: (a) mesh; (b) observation cross-section layout.

Table 2. Position parameters of characteristic sections (Note: The centerline of the forebay was taken as the axis of symmetry; in the vertical ((Z)) direction, the coordinate origin was set at 2.38 m below the water surface).

Longitudinal Sections		Transverse Sections		Horizontal Planes	
Section Name	Section Position m	Section Name	Section Position m	Section Name	Section Position m
Y1	−8	X1	0	Z1	−1.38
Y2	−4	X2	−9	Z2	2.26
Y3	0				
Y4	4				
Y5	8				

To verify the accuracy of the calculation method and numerical model, the characteristic line formed by the intersection of transverse section X1 and horizontal plane Z1 was selected as the object of analysis, and the simulated values along this characteristic line were compared with the measured values, as shown in Figure 3.

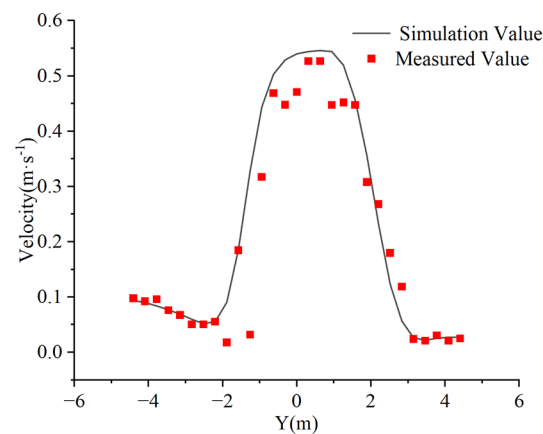


Figure 3. Comparison between measured and simulated flow velocities.

To further verify the reliability of the numerical model, Figure 4 shows the flow-velocity contours at sections Y2 and Y4, together with comparisons between the simulated and measured values along characteristic lines L_{Y2-Z1} and L_{Y4-Z1} , which are formed by the intersections of sections Y2 and Y4 with plane Z1, respectively.

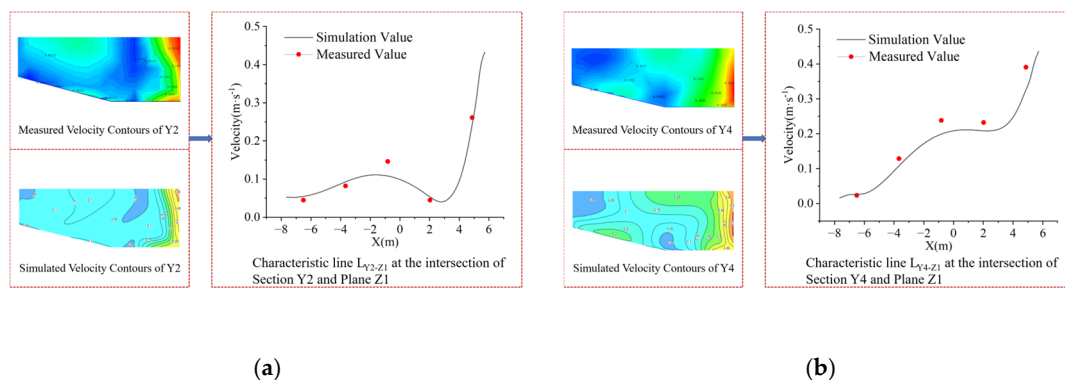


Figure 4. Comparison of measured and simulated velocity contours in longitudinal sections: (a) measured and simulated values at section Y2; (b) measured and simulated values at section Y4.

To quantitatively evaluate the agreement between the simulated and measured velocities, the pointwise error was first calculated as:

$$e_i = u_{s,i} - u_{m,i} \quad (4)$$

where $u_{s,i}$ and $u_{m,i}$ are the simulated and measured velocities at measurement point i , respectively.

The pointwise relative error was defined as:

$$\delta_i = \frac{|u_{s,i} - u_{m,i}|}{u_{m,i}} \times 100\% \quad (5)$$

To further evaluate the overall accuracy of the numerical model, the mean absolute error, root mean square error, standard error, and coefficient of determination were calculated as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |u_{s,i} - u_{m,i}| \quad (6)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (u_{s,i} - u_{m,i})^2} \quad (7)$$

$$SE = \frac{1}{\sqrt{n}} \sqrt{\frac{\sum_{i=1}^n (e_i - \bar{e})^2}{n-1}} \quad (8)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (u_{s,i} - u_{m,i})^2}{\sum_{i=1}^n (u_{m,i} - \bar{u}_m)^2} \quad (9)$$

where n is the number of measurement points, e_i is the pointwise error, $\bar{e}$ is the mean error, and $\bar{u}_m$ is the mean measured velocity. The MAE, RMSE, and SE have units of m/s, whereas the relative error and R^2 are dimensionless.

The quantitative validation results are summarized in Table 3. A total of 39 measurement points were used for model validation, including 29 points along L_{X1-Z1} and 5 points each along L_{Y2-Z1} and L_{Y4-Z1}. The mean relative errors of the three validation lines were 19.53%, 17.66%, and 15.99%, respectively. The MAE values ranged from 0.017 to 0.039 m/s, and the RMSE values ranged from 0.020 to 0.071 m/s, indicating that the absolute differences between the simulated and measured flow velocities were relatively small. In addition, the SE values ranged from 0.009 to 0.012 m/s, suggesting good stability of the errors. The (R^2) values were all close to 0.9, indicating good agreement between the measured and simulated results. Therefore, the established numerical model has good reliability and can be used for subsequent analyses of the flow-field and sediment transport characteristics.

Table 3. Quantitative comparison between measured and simulated velocities.

Validation Line	Number of Points	Mean Relative Error %	MAE m/s	RMSE m/s	SE m/s	R^2
L _{X1-Z1}	29	19.53	0.039	0.071	0.012	0.88
L _{Y2-Z1}	5	17.66	0.017	0.020	0.009	0.91
L _{Y4-Z1}	5	15.99	0.030	0.036	0.011	0.87

4. Numerical Simulation Results and Analysis

Using the Mixture water–sediment two-phase flow numerical model, numerical simulations were conducted for the pumping-station forebay, and the flow-field distribution characteristics at horizontal plane Z1 were extracted, as shown in Figure 5a. As shown in the figure, the mainstream region in the forward-facing forebay is characterized by relatively high flow velocity and a uniform velocity distribution. In the forward-facing forebay, the sudden change in the geometric boundary leads to energy conversion within the flow and induces a local pressure gradient. Driven by the resulting pressure difference, the flow exhibits obvious separation, with vortices forming on both the left and right sides. Moreover, because pump units B# and C# are in operation, the vortex on the left side is larger than that on the right side. Vortices exert a significant influence on sediment transport and deposition. In the vortical regions, the flow velocity decreases, causing sediment particles to be retained under low-velocity conditions. The sediment concentration distribution shown in Figure 5b further confirms this pattern, indicating that vortical regions are the main areas of sediment accumulation. The numerical simulation results reveal the relationship between vortical structures in the forebay and sediment transport and deposition. Therefore, to reduce the vortex scale and decrease the likelihood of sediment settling in the forebay, this study proposes the implementation of rectification measures to improve the forebay flow structure.

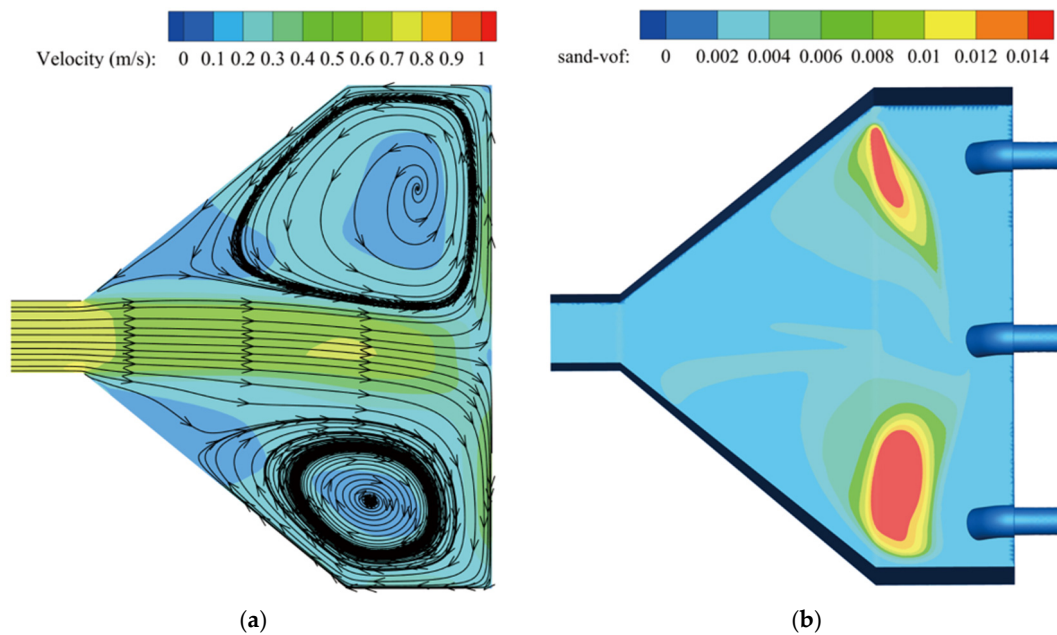


Figure 5. Calculated results of the flow field and sediment concentration in the forebay under the baseline condition: (a) flow-field distribution; (b) sediment concentration distribution.

Based on the experience reported in previous studies, splayed guide walls were installed in the sloping inlet section to further improve the flow structure of the forebay. The guide walls affect both the vortex scale and sediment distribution in the forebay, and their layout is a key factor governing the forebay flow structure and sediment transport. To improve the rectification effect of the splayed guide walls on the forebay flow pattern, five groups of guide-wall deflection angles relative to the x -axis were designed in this study, and the corresponding layouts are shown in Figure 6, detailed parameters are provided in Table 4.

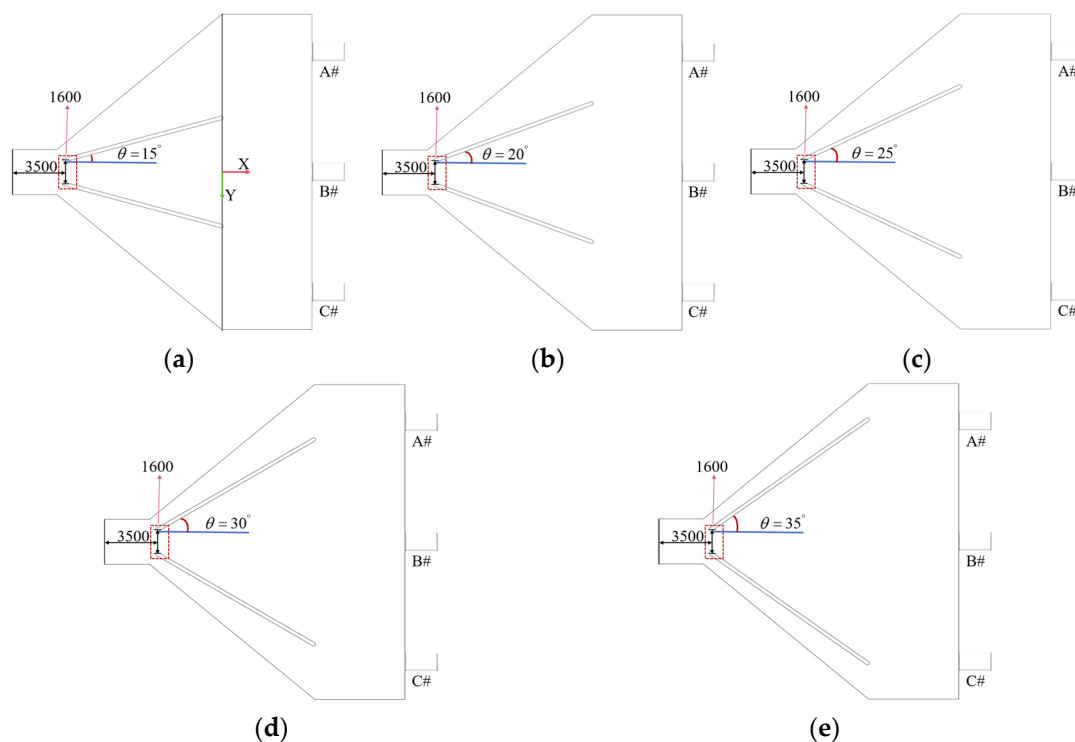


Figure 6. Schematic layout of the splayed guide walls: (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5 (Note: The unit is mm).

Table 4. Guide-wall layout parameters for different schemes.

Design Condition	Distance from the Guide Wall to the Inlet m	Guide-Wall Deflection Angle θ Relative to the x -Axis
Baseline condition	-	-
1	3.5	15°
2	3.5	20°
3	3.5	25°
4	3.5	30°
5	3.5	35°

4.1. Multi-Criteria Screening Method for Guide-Wall Deflection-Angle Optimization

The purpose of guide-wall optimization in this study was not to maximize a single hydraulic index, but to reduce sediment deposition in the forebay while maintaining acceptable inlet hydraulic conditions for the operating pump units. Therefore, a sediment-control-oriented hierarchical screening method was adopted instead of a weighted scoring method. No subjective weights were assigned to the evaluation indices.

The screening procedure was defined as follows. First, sediment-control performance was taken as the primary criterion, including the reduction in the potential deposition area and the sediment deposition efficiency. The sediment volume-fraction threshold of 0.0015 was used as the primary criterion for identifying the overall potential deposition range, whereas the threshold of 0.002 was used as a supplementary criterion for identifying local high-concentration sediment-enrichment regions. Second, hydraulic performance was treated as a constraint. The recommended scheme should not cause obvious reappearance of large-scale vortices in the intake basin, and the axial velocity uniformities of pumps B# and C# should not be lower than those under the baseline condition. Third, among the schemes satisfying the above conditions, the recirculation area, recirculation volume, global recirculation coefficient, and the coordination of the inlet velocity uniformities of pumps B# and C# were compared comprehensively.

Under this framework, the selected scheme should be understood as a recommended sediment-control-oriented scheme rather than the scheme that gives the best value for every individual indicator.

4.2. Influence of the Guide Wall on the Planar Flow Field in the Forebay

As a key flow passage connecting the diversion channel and the pump suction inlet, the forebay plays a crucial role in determining the rationality of the internal flow field, which directly affects the inflow conditions, stable operation, and utilization efficiency of the pump. During the actual operation of a pumping station, vortex structures are prone to forming in the forebay due to flow separation and recirculation. In particular, downstream vortices near the pump suction inlet may lead to a series of engineering problems. The low-pressure region at the vortex core can entrain air and induce cavitation, resulting in surface damage to the pump impeller, intensified vibration, and excessive noise. Moreover, unsteady vortex motion can induce inflow distortion at the pump inlet, disrupt the force balance of the impeller, and reduce the operating efficiency of the unit; in severe cases, it may even result in shutdown failures. The velocity contours at horizontal sections Z1 and Z2 under six conditions based on the numerical simulations, together with the corresponding vortex migration characteristics, are shown in Figure 7.

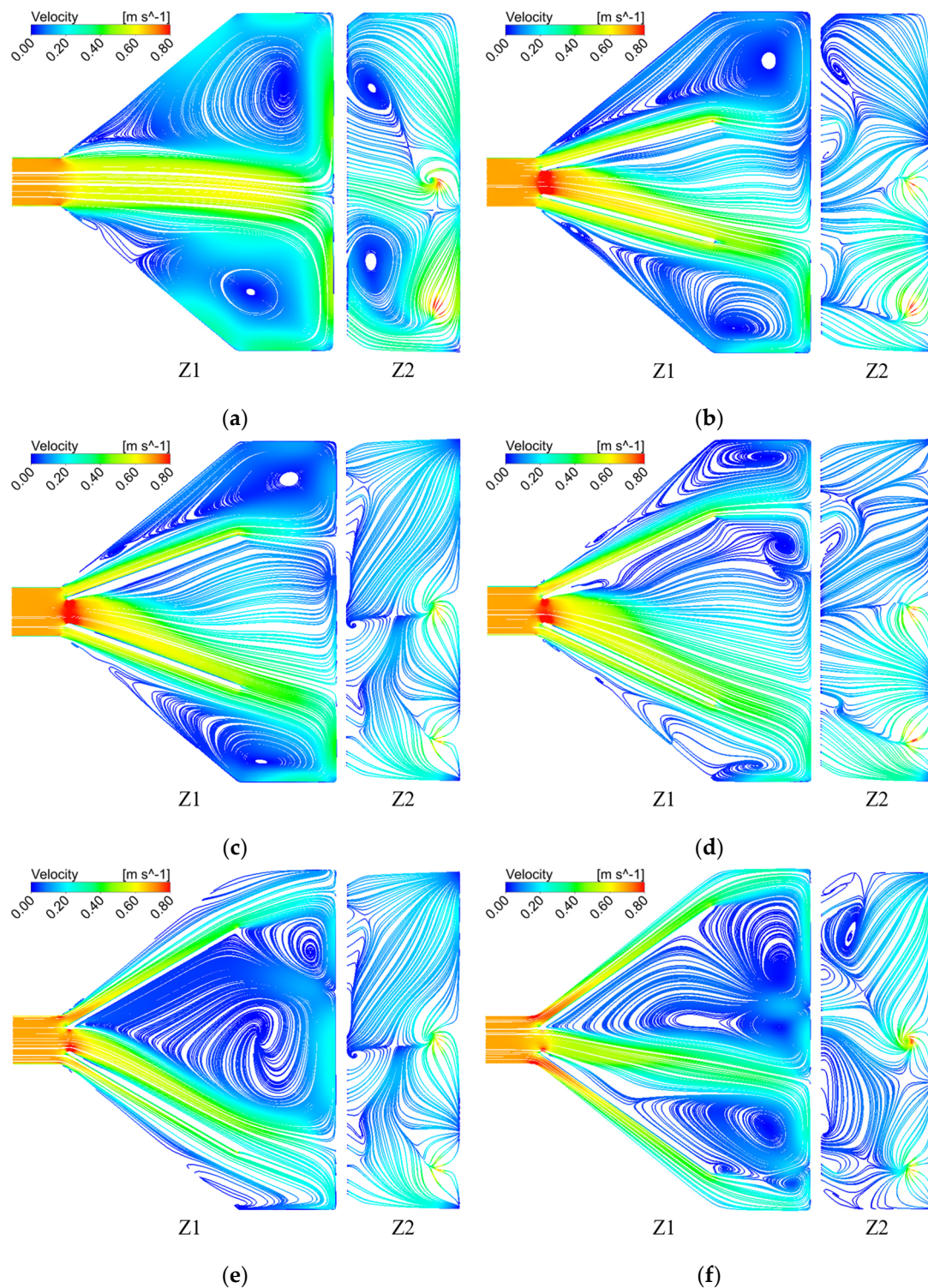


Figure 7. Flow structure distributions at different water depths: (a) baseline condition; (b) condition 1; (c) condition 2; (d) condition 3; (e) condition 4; (f) condition 5. The flow-field distributions on planes Z1 and Z2 are shown for each condition.

The flow-field distribution on plane Z1 indicates that, in the absence of a guide wall, large-scale low-velocity recirculation zones occur on both sides of the forebay. The flow exhibits a swirling motion, which constricts the passage area of the mainstream region and leads to locally high velocities within the mainstream. As a result, high-velocity zones and recirculation zones coexist, and the velocity distribution is highly nonuniform. The high-velocity region is concentrated in the middle of the forebay, while large low-velocity recirculation zones develop on both sides. These recirculation zones may cause sediment

deposition, resulting in poor flow conditions near the suction pipe and adversely affecting the operation of the unit. When the guide-wall deflection angle θ is $15\text{--}20^\circ$, the flow field is improved to some extent. The width of the mainstream region increases significantly, and the flow spreads sufficiently in the transverse direction of the forebay, exhibiting a broad and smooth distribution pattern. The recirculation zones on both sides gradually shrink but are not completely eliminated; therefore, the risk of sediment deposition remains. At a guide-wall deflection angle of $\theta = 25^\circ$, the flow pattern in the forebay is nearly uniform and smooth, with a significant reduction in the vortex scale on both sides. This effectively suppresses sediment retention and facilitates smooth inflow into the suction pipe. At guide-wall deflection angles of $\theta = 30\text{--}35^\circ$, the velocity distribution becomes progressively less uniform. High-velocity regions appear on both sides, whereas relatively low velocities occur in the central region, resulting in a new velocity gradient. In addition, new recirculation zones develop in the region between the guide wall and the side wall, causing unfavorable flow patterns to re-emerge.

The hydraulic regulation mechanism of the guide wall is closely related to the redistribution of streamwise and transverse momentum in the forebay. When the guide-wall deflection angle (θ) is small, such as 15° or 20° , the guide wall is nearly parallel to the incoming mainstream. Under this condition, the transverse deflection effect of the guide wall is weak, and the lateral momentum supplied to the near-wall regions is insufficient. As a result, the mainstream remains concentrated in the central part of the forebay, while the low-velocity regions near both side walls cannot be effectively replenished by high-momentum flow. The original wall-separated recirculation zones are therefore only partially compressed rather than completely eliminated. This explains why the flow-rectification effect is limited under small-angle guide-wall schemes. When the guide-wall deflection angle (θ) increases to 25° , the guide wall provides a more appropriate lateral guidance effect. The incoming flow is gradually diffused toward both sides of the forebay, and the transverse momentum exchange between the mainstream region and the near-wall low-velocity regions is enhanced. Meanwhile, the angle is not excessively large, so obvious flow separation does not occur behind the guide wall. Therefore, the mainstream region is broadened, the velocity gradient between the central flow and the near-wall regions is weakened, and the wall-separated recirculation zones are effectively suppressed. This indicates that the $\theta = 25^\circ$ scheme achieves a favorable balance between flow diffusion and flow stability. When the guide-wall deflection angle (θ) further increases to $30\text{--}35^\circ$, the guide wall imposes excessive lateral deflection on the incoming flow. The flow is forced to turn rapidly along the guide wall, producing a strong transverse velocity component and a local adverse pressure gradient near the downstream end of the guide wall. After the flow passes the guide-wall tip, the sudden expansion and the strong shear between the high-velocity guided flow and the adjacent low-velocity water promote local flow separation. Consequently, secondary recirculation zones may form in the region behind the guide wall or within the included-angle region between the guide wall and the side wall. In addition, the excessive diffusion of the mainstream may cause local flow impingement on the side walls, further enhancing transverse velocity gradients and vortex development. Therefore, an excessively large guide-wall angle does not continuously improve the flow pattern; instead, it may induce new unfavorable recirculation structures.

Analysis of the flow field at the Z2 plane shows that, under the baseline condition, vortices are mainly concentrated in the intake basin near the suction pipes. The vortex cores are located close to the vertical projections of the pump suction inlets, directly affecting pump operation and aggravating vibration and noise. In cases 1, 2, 3, and 4, no vortices appeared in the intake basin, and the flow pattern was uniform and smooth. The flow velocity near the pump suction pipes ranged from 0.3 to 0.4 m/s, which was sufficient to effectively carry sediment smoothly through the suction pipes. In case 5, however, ow-

ing to the excessively large guide-wall deflection angle θ , vortices reappeared on the left side of the intake basin, and the uniformity of the velocity distribution began to gradually deteriorate.

Based on the axial velocity and reverse-flow criteria, the recirculation area and recirculation volume were calculated, as shown in Table 5. The recirculation area under the baseline condition was 106.62 m². When the guide-wall deflection angle θ was 15°, 20°, 25°, 30°, and 35°, the recirculation area was reduced by 11.32%, 21.08%, 23.23%, 18.89%, and 11.35%, respectively, compared with that under the baseline condition. It can thus be concluded that adjusting the guide-wall deflection angle θ can effectively improve the flow pattern in the forebay and weaken boundary-layer separation. For the forward-facing forebay of the first-stage Xin Zhuangji Pumping Station, a guide-wall deflection angle of $\theta = 25^\circ$ is considered suitable. Under this condition, the recirculation area is reduced to the greatest extent, effectively weakening the sediment accumulation effect. When the guide-wall deflection angle θ is no greater than 20° or no less than 30°, the improvement effect on the flow pattern becomes less stable.

Table 5. Recirculation area on horizontal plane Z1 and recirculation volume of the forebay under different cases.

Guide-Wall Deflection Angle θ	Recirculation Area (m ²)	Reduction Ratio of Recirculation Area Compared with the Baseline Condition %	Recirculation Volume (m ³)	Percentage Reduction in Recirculation Volume Relative to the Baseline Condition %
Baseline condition	106.62	-	774.161	-
15°	94.55	11.32	648.801	16.19
20°	84.15	21.08	637.613	17.64
25°	81.85	23.23	614.479	20.63
30°	86.48	18.89	636.397	17.80
35°	94.52	11.35	591.407	23.61

To further quantify the flow-rectifying effect of the guide wall, the axial velocity distribution uniformity and the global recirculation coefficient were adopted as evaluation indicators for the optimization performance. In the formulas, $\bar{v}_a$ denotes the axial velocity distribution uniformity at each suction pipe inlet [22], while R represents the global recirculation coefficient. The corresponding formulas are expressed as follows [23]:

$$\bar{v}_a = \left[1 - \frac{1}{\bar{u}_a} \sqrt{\frac{\sum (u_{ai} - \bar{u}_a)^2}{m}} \right] \times 100\% \quad (10)$$

$$R = \left(1 - \frac{A_u}{A} \right) \times 100\% \quad (11)$$

where $\bar{u}_a$ is the mean axial velocity at the pump inlet section, m/s; u_{ai} is the axial velocity at the data points sampled on the pump inlet section, m/s; (m) is the number of data

points sampled on the pump inlet section; A_u is the recirculation area of the section, m^2 ; and (A) is the cross-sectional area, m^2 .

Table 6 presents the variations in the axial velocity distribution uniformity at the suction-pipe sections of pumps B# and C#, as well as the global recirculation coefficient (R) on plane Z1, under different guide-wall deflection-angle schemes. A velocity uniformity closer to 100% indicates a more uniform axial velocity distribution at the suction-pipe section, which is more favorable for the efficient and stable operation of the pump units. A larger global recirculation coefficient (R), closer to 100%, indicates a smaller recirculation region and a more stable intake flow pattern.

As shown in Table 6, under the baseline condition, the global recirculation coefficient (R) on plane Z1 was 60.07%, while the axial velocity distribution uniformities at the suction-pipe sections of pumps B# and C# were 66.38% and 53.26%, respectively. This indicates that the velocity distribution uniformity at the inlet sections of the two operating pumps was relatively poor under the baseline condition, especially for pump C#. The low velocity uniformity reflects an uneven distribution of flow energy, which may induce flow disorder inside the pumps and is therefore unfavorable for the long-term efficient and stable operation of the pump units.

With the adjustment of the guide-wall deflection angle θ , the axial velocity distribution uniformity at the sections of pumps B# and C# generally exhibited a fluctuating upward trend. For pump B#, the velocity uniformity reached its maximum value of 82.62% under the ($\theta = 30^\circ$) scheme, representing an increase of approximately 24.47% compared with the baseline condition. This indicates that this scheme provided the most significant improvement in the inlet velocity distribution of pump B#. In comparison, the velocity uniformity of pump B# under the ($\theta = 25^\circ$) scheme was 71.23%. Although this value was not the highest, it was still higher than that under the baseline condition, indicating that this scheme did not deteriorate the inlet hydraulic performance of pump B#. For pump C#, the ($\theta = 25^\circ$) and ($\theta = 35^\circ$) schemes showed relatively prominent optimization effects, increasing the velocity uniformity to 80.61% and 81.81%, respectively. These values correspond to increases of approximately 51.35% and 53.61% compared with the baseline condition, indicating that both schemes significantly improved the velocity distribution uniformity at the suction-pipe section of pump C#.

In terms of the global recirculation coefficient (R), the ($\theta = 25^\circ$) scheme achieved the maximum value among all schemes, reaching 68.69%, which represents an increase of approximately 14.35% compared with the baseline condition. This indicates that this scheme can effectively reduce the recirculation region on plane Z1 and improve the overall intake flow pattern. Although the velocity uniformity of pump C# under the ($\theta = 35^\circ$) scheme was slightly higher than that under the ($\theta = 25^\circ$) scheme, its global recirculation coefficient on plane Z1 decreased to 63.76%, indicating that its overall recirculation suppression effect was weaker than that of the ($\theta = 25^\circ$) scheme. In addition, although the ($\theta = 30^\circ$) scheme produced the highest velocity uniformity for pump B#, the velocity uniformity of pump C# was only 59.36%, indicating poor coordination of inlet conditions between the two operating pumps.

Therefore, the ($\theta = 25^\circ$) scheme did not achieve the optimum value for every individual hydraulic indicator. Instead, while ensuring that the inlet hydraulic performance of pump B# was not lower than that under the baseline condition, it significantly improved the inlet velocity distribution of pump C# and achieved the best overall recirculation suppression effect. Considering the coordination of the inlet conditions of pumps B# and C# and the overall flow pattern on plane Z1, the ($\theta = 25^\circ$) scheme can be regarded as a relatively reasonable and balanced hydraulic optimization scheme.

Table 6. Axial velocity distribution uniformity at the pump suction-pipe sections and global recirculation coefficient (R) at section Z1 under different schemes (%).

Pump Number	Baseline Condition	15°	20°	25°	30°	35°
B#	66.38	78.10	81.03	71.23	82.62	73.31
C#	53.26	57.00	69.48	80.61	59.36	81.81
Global recirculation coefficient R	60.07	63.87	67.83	68.69	66.88	63.76

4.3. Influence of the Guide Wall on the Velocity Distribution in Longitudinal Sections

To further reveal the influence of the splayed guide wall on the longitudinal velocity distribution in the forebay, the velocity distributions on three longitudinal sections, namely Y1, Y3, and Y5, were analyzed under different angles between the guide wall and the x -axis. Meanwhile, the velocity variations along the characteristic lines L_{Y1-Z1} , L_{Y3-Z1} , and L_{Y5-Z1} were extracted, as shown in Figure 8.

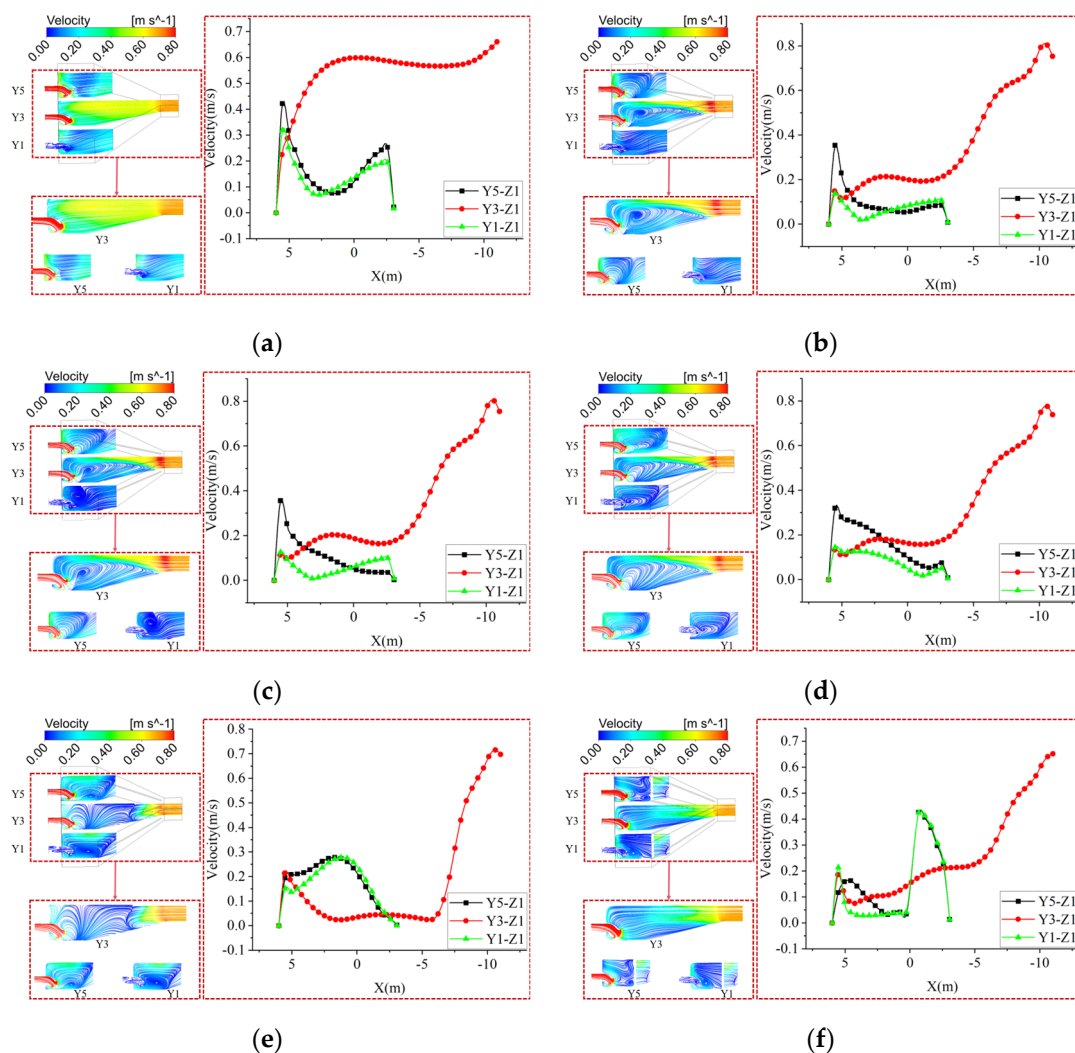
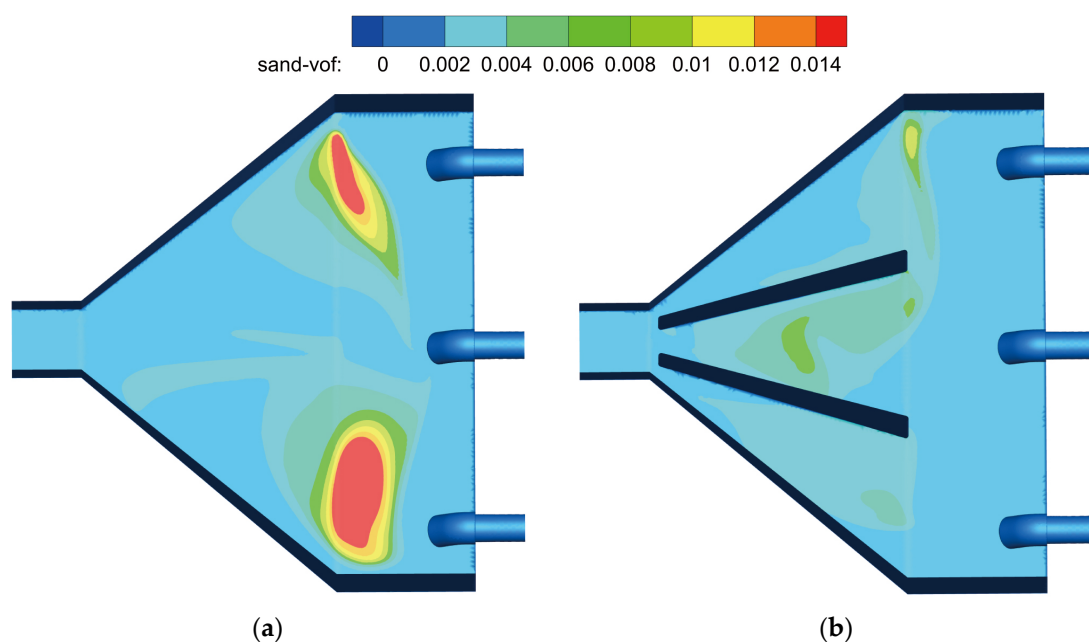


Figure 8. Velocity distributions at different longitudinal sections: (a) velocity distribution under the baseline condition; (b) velocity distribution under case 1; (c) velocity distribution under case 2; (d) velocity distribution under case 3; (e) velocity distribution under case 4; (f) velocity distribution under case 5.

As shown by the longitudinal-section velocity contours and the corresponding characteristic-line velocity curves under different cases in Figure 8, the deflection angle θ of the splayed guide walls has a significant regulatory effect on the longitudinal flow-field structure in the forebay. Under the baseline condition, the velocity distribution in the mainstream region is relatively concentrated, and the high-velocity region mainly develops along the main-channel direction. Obvious velocity-gradient variations occur in local regions, indicating that the flow at this section is strongly affected by the topography and boundary conditions. Compared with the baseline condition, the velocity distributions under cases 1–5 exhibit varying degrees of adjustment, and the location, extent, and continuity of the high-velocity regions differ among the cases. In case 1, the velocity variation is relatively small, and the overall flow pattern remains similar to that under the baseline condition. In case 2, the high-velocity region contracts or shifts to some extent, while the local low-velocity region expands, indicating that this case has a certain weakening effect on the flow. In case 3, the velocity distribution becomes more uniform, and local abrupt variations are weakened, suggesting that the longitudinal flow continuity is improved. In case 4, the low-velocity region further expands, the high-velocity region is significantly compressed, and the flow energy attenuation along the flow path becomes more pronounced. Case 5 exhibits the most obvious velocity-adjustment characteristics, with substantial changes in both the extent and intensity of the high-velocity region. Local recirculation or stagnant zones may increase, indicating that this case has the most significant influence on the longitudinal flow structure. Overall, the different cases exert regulatory effects on the velocity field at the longitudinal sections. With changes in the cases, the flow gradually shifts from a relatively concentrated high-velocity transport state under the baseline condition to a low-velocity, dispersed, or more uniform flow pattern. This indicates that adjustments to the engineering layout or boundary conditions can effectively alter the hydrodynamic distribution characteristics within the sections.

4.4. Distribution Characteristics of Sediment Volume Concentration in the Forebay

To investigate the sediment distribution patterns in the forebay, the sediment volume fraction was selected as the analysis index, and numerical simulations were conducted to characterize the sediment distribution. The sediment distribution maps are shown in Figure 9.



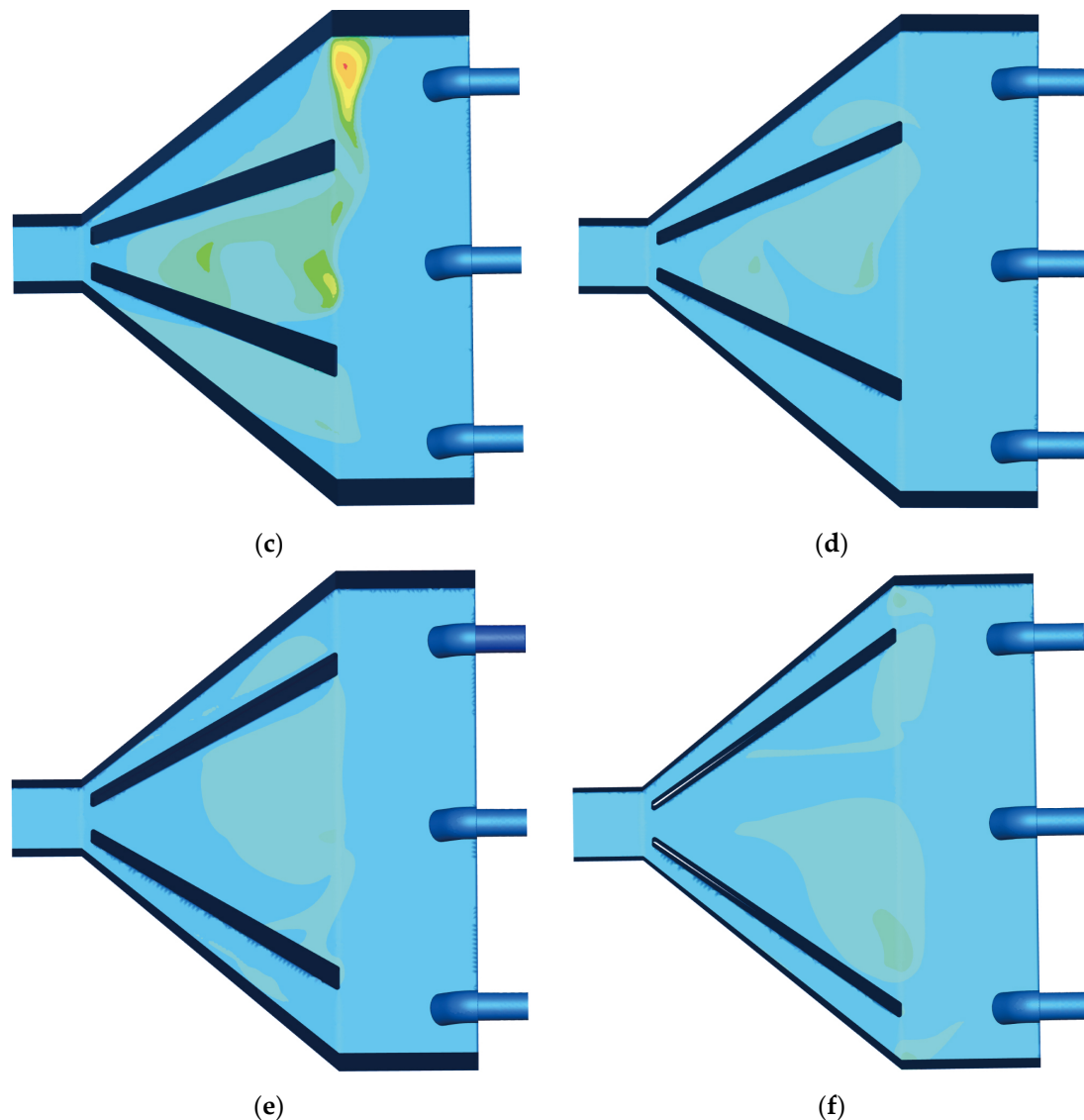


Figure 9. Sediment distributions under different cases: (a) sediment distribution under the baseline condition; (b) sediment distribution under case 1; (c) sediment distribution under case 2; (d) sediment distribution under case 3; (e) sediment distribution under case 4; (f) sediment distribution under case 5.

As shown in Figure 9a, without guide walls, sediment deposition in the forebay is mainly distributed at the forebay inlet and in the regions on both sides of the intake basin. The high-sediment-concentration regions are primarily concentrated near the front ends of the suction pipes of pump units A# and C#. At the inlet section, recirculation zones are formed due to abrupt changes in the flow pattern, which weaken the sediment-carrying capacity of the flow and lead to the settling and deposition of suspended sediment. In the near-unit regions on both sides of the intake basin, the flow is affected by outlet-flow disturbances, resulting in insufficient sediment-carrying capacity and the formation of obvious high-sediment-concentration zones.

As shown in cases 1 and 2, the high-sediment-concentration regions migrate toward the vicinity of the guide-wall structures and are mainly distributed along the inner sides of the guide walls in the forebay. The distribution pattern of the high-sediment-concentration regions in the near-unit regions on both sides of the intake basin is significantly improved. However, a small-scale recirculation zone still remains on the left side, causing local sediment accumulation. Under cases 3 and 4, the spatial distribution of the sediment-concentration regions becomes more dispersed, and the intensity of the high-sediment-

concentration regions in the near-unit regions on both sides of the intake basin is substantially weakened. The overall flow pattern within the structure tends to become more uniform, and the suspended-sediment transport efficiency is significantly improved. In case 5, however, high-sediment-concentration regions reappear in local areas near the downstream end of the forebay, and the extent of sediment accumulation expands. This indicates that when the guide-wall deflection angle θ is excessively large, the guide-wall structures impose excessive constraints on the flow, which instead induces secondary recirculation and leads to a reduction in the local sediment-carrying capacity.

According to the simulation results shown in Figure 9, the sediment volume fraction can be used to identify regions with relative sediment enrichment and potential deposition risk within the computational domain. In this study, the term “deposition area” does not refer to the geomorphic deposition area associated with actual changes in bed elevation, but rather to the area in the numerical simulation results where the sediment volume fraction exceeds a specified threshold. Since the inlet sediment volume fraction was 0.001, a threshold of 0.0015, which is higher than the inlet sediment volume fraction, was selected as the primary criterion to avoid misclassifying regions close to the inlet background concentration as deposition areas. As a relatively low threshold above the inlet sediment volume fraction, 0.0015 can more comprehensively reflect the overall potential deposition range and is therefore more suitable as the main criterion for evaluating sediment-reduction performance. In addition, a higher threshold of 0.002 was selected as a supplementary criterion to examine the variation in sediment-reduction performance among different cases under different threshold conditions.

The supplementary comparison results show that, when 0.0015 was used as the threshold criterion, the deposition areas under cases 1, 2, 3, 4, and 5 were reduced by 16.55%, 15.22%, 53.67%, 51.34%, and 33.16%, respectively, compared with the baseline condition. Among them, case 3 exhibited the largest reduction in deposition area, indicating that it had the most significant effect in reducing the overall potential deposition range. When 0.002 was used as the threshold criterion, the deposition areas under cases 1, 2, 3, 4, and 5 were reduced by 15.42%, 6.29%, 61.38%, 65.39%, and 49.63%, respectively, compared with the baseline condition. Although the reduction ratio of the deposition area under case 4 was slightly higher than that under case 3 at this threshold, case 3 still showed a significant sediment-reduction effect, indicating that its sediment-reduction performance remained relatively stable under different threshold conditions.

The main objective of guide-wall deflection-angle optimization in this study was to reduce the extent of sediment deposition, and the threshold of 0.0015 was more suitable as the primary evaluation criterion for the overall potential deposition range. Under this primary criterion, the guide-wall scheme with ($\theta = 25^\circ$), namely case 3, achieved the largest ratio of reduction in deposition area. Meanwhile, under the threshold of 0.002, case 3 still maintained a relatively strong sediment-reduction effect, further demonstrating the stability and effectiveness of this guide-wall scheme in sediment-deposition control.

The ranking of cases 3 and 4 changed when the sediment volume-fraction threshold increased from 0.0015 to 0.002, indicating that the quantitative reduction ratio and the identification of the best-performing scheme were sensitive to the selected threshold. Nevertheless, cases 3 and 4 remained the two leading schemes under both threshold criteria. Case 3 was recommended not solely because of the deposition-area result at a single threshold, but also because it provided a comparatively balanced performance when the overall potential deposition range, local high-concentration sediment-enrichment regions, recirculation characteristics, and inlet hydraulic conditions of the operating pumps were considered together.

4.5. Vertical Volume-Fraction Uniformity

The sediment transport efficiency and stability in the forebay of a forward-facing pumping station directly determine the operational safety and service life of the pumping

station. The spatial distribution uniformity of the sediment volume fraction is one of the key indicators for evaluating the sediment transport capacity of the forebay. Figure 10 presents the vertical sediment distribution characteristics under different cases.

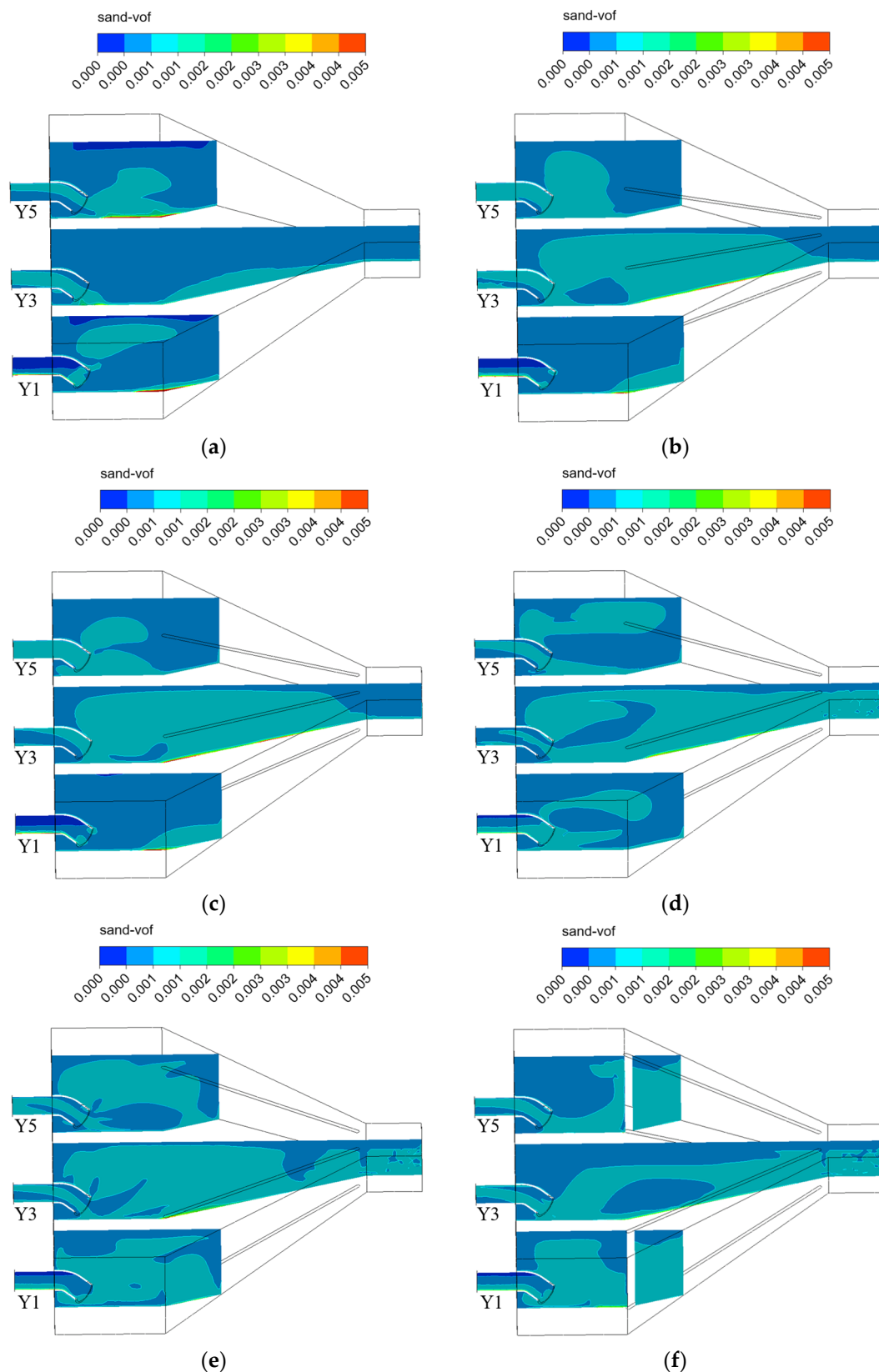


Figure 10. Vertical distribution characteristics of sediment volume concentration at different sections: (a) vertical sediment distribution characteristics under the baseline condition; (b) vertical sediment distribution characteristics under case 1; (c) vertical sediment distribution characteristics un-

der case 2; (d) vertical sediment distribution characteristics under case 3; (e) vertical sediment distribution characteristics under case 4; (f) vertical sediment distribution characteristics under case 5.

Under the baseline condition without guide walls, the sediment volume concentration at the lateral sections Y1 and Y5 is higher than that at the middle section Y3, whereas the near-surface sediment concentration at sections Y1 and Y5 is extremely low. This is mainly because the mainstream velocity is relatively high, resulting in a strong sediment-carrying capacity, which makes sediment difficult to settle in this region. After the mainstream reaches the intake basin, it disperses toward both sides. In addition, under the influence of the side walls, two large near-wall low-velocity recirculation zones are formed in the intake basin. The flow velocity in these regions is relatively low, and the sediment-carrying capacity is weak, leading to continuous sediment settling in these areas. Under cases 1–5, owing to the influence of the guide walls, the mainstream flow is effectively diffused, and the flow becomes relatively uniform throughout the entire flow field, thereby avoiding the formation of large low-velocity recirculation zones in the forebay. In addition, affected by the bed slope and flow diffusion in the forebay, the water depth gradually increases along the flow path as the flow enters the intake basin, while the flow velocity gradually decreases. Consequently, the sediment-carrying capacity of the flow progressively weakens, resulting in different degrees of sediment deposition within the forebay.

To evaluate the effectiveness of the guide-wall arrangement, the sediment deposition efficiency, η , was introduced. A lower sediment deposition efficiency indicates better sediment-control performance.

It is calculated as follows [24]:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \quad (12)$$

where C_{in} and C_{out} denote the average sediment volume concentrations at the forebay inlet and the suction-pipe outlets, respectively.

As shown in Figure 11, the sediment deposition efficiency under the baseline condition was 0.185, indicating that the sediment-carrying capacity of the flow in the forebay was relatively weak in the absence of guide walls, resulting in a high risk of sediment deposition within the basin. When the guide-wall deflection angles θ were adjusted to 15°, 20°, 25°, 30°, and 35°, the corresponding sediment deposition efficiencies were 0.130, 0.137, 0.033, 0.056, and 0.047, respectively, all of which were lower than that under the baseline condition. This suggests that optimizing the guide-wall deflection angle θ can effectively enhance the sediment-carrying capacity of the flow and thereby reduce sediment deposition efficiency. The sediment-control performance varied significantly with the guide-wall deflection angle. At $\theta = 25^\circ$, the sediment deposition efficiency decreased to 0.033, corresponding to an 82.16% reduction compared with the baseline condition. This angle exhibited the most significant sediment-control effect among the analyzed cases and effectively alleviated sediment deposition in the forebay.

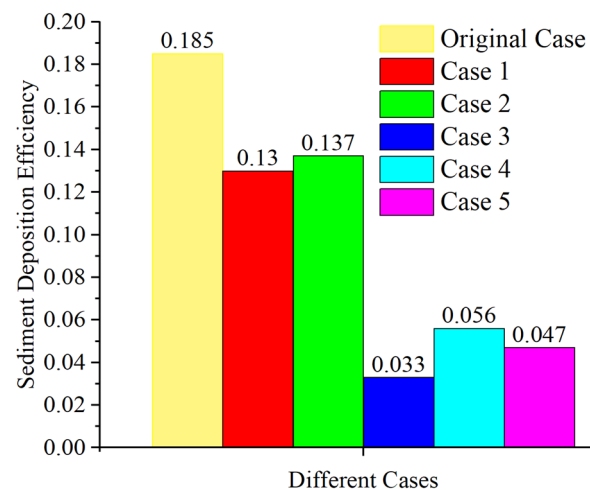


Figure 11. Sediment deposition efficiency for each case.

The reduction in potential sediment retention within the forebay is accompanied by an increase in the proportion of sediment transported through the suction-pipe outlets. This result reflects an engineering trade-off between reducing sediment deposition in the forebay and limiting sediment exposure of the pump units. Reducing sediment retention within the forebay helps maintain the effective flow-passage area, suppress local deposition near the suction pipes, and reduce the frequency of forebay dredging. In contrast, a higher sediment throughflow may increase the likelihood of contact between sediment particles and the impeller, guide vanes, pump casing, and other flow-passage components, thereby potentially aggravating abrasive wear. The actual abrasion risk depends not only on the sediment concentration entering the pumps, but also on particle size, mineral hardness, particle shape, impact velocity, impact angle, and the internal flow structure of the pumps.

In this project, fine particles smaller than 66.87 μm accounted for 95.83% of the total sediment, and the median particle size was 15 μm . Therefore, the guide-wall layout mainly altered the sediment transport path rather than eliminating sediment-related operational risks. Since the computational domain in this study did not include the internal flow passages of the pumps and no abrasion model was adopted, the resulting wear of pump components could not be quantitatively evaluated. Therefore, the recommended ($\theta = 25^\circ$) scheme should be understood as a forebay sediment-retention control scheme under the investigated operating condition, rather than a scheme that simultaneously minimizes both forebay deposition and pump wear.

In engineering applications, the guide-wall layout should be implemented in combination with sediment concentration monitoring at the suction-pipe sections, regular inspection of pump components, wear-resistant materials or coatings, upstream desilting facilities, and appropriate flushing or maintenance strategies. Future studies should couple the sediment transport model in the forebay with the internal pump-flow and abrasion models to identify a system-level compromise between reducing forebay deposition and limiting sediment-induced wear of pump units.

5. Conclusions

- (1) In the forward-facing forebay of the first-stage Xin Zhuangji Pumping Station in Hong Sibü, Ningxia, the large diffusion angle makes the flow prone to separation, resulting in extensive wall-separated recirculation zones on both sides. The mainstream region is narrow and characterized by relatively high velocity, and the velocity distribution is extremely nonuniform. In the recirculation zones, the sediment-carrying capacity of the flow is weak, leading to substantial sediment deposition,

which is mainly concentrated on both sides of the intake basin near the suction pipes and seriously affects the operating efficiency and safety of the pumping station.

- (2) By installing splayed guide walls in the forebay, this flow-rectification measure can divert and guide the incoming flow, broaden the mainstream region, suppress recirculation on both sides, and equalize the sectional velocity distribution. As a result, the sediment-carrying capacity of the flow is effectively enhanced, and sediment deposition is reduced. When the guide-wall deflection angle θ is smaller than 20° , the flow-guiding effect is insufficient; when the guide-wall deflection angle θ is larger than 30° , secondary recirculation is likely to be induced. Therefore, under the investigated operating condition, neither angle range provided a favorable overall regulation effect.
- (3) The optimal guide-wall deflection angle θ varied depending on the evaluation indicator. The ($\theta = 30^\circ$) scheme produced the highest axial velocity uniformity for pump B#, whereas the ($\theta = 35^\circ$) scheme produced the highest axial velocity uniformity for pump C# and achieved the largest reduction in recirculation volume. However, considering that the main objective of this study was sediment deposition control, the ($\theta = 25^\circ$) scheme exhibited the most stable comprehensive performance. Under this scheme, the recirculation area on plane Z1 decreased by 23.23%, the global recirculation coefficient reached 68.69%, the sediment deposition efficiency decreased to 0.033, and the axial velocity uniformities of pumps B# and C# were 71.23% and 80.61%, respectively. Therefore, under the investigated operating condition, the ($\theta = 25^\circ$) scheme is recommended as the scheme oriented toward sediment-reduction control.
- (4) Engineering application value and limitations: Based on the numerical simulations of water–sediment two-phase flow, this study identifies a preferred splayed guide-wall deflection angle of $\theta = 25^\circ$ for the forebay of the first-stage Xin Zhuangji Pumping Station under the tested geometry and operating condition. The results provide a technical reference for improving the flow pattern and reducing sediment-retention risk in similar forward-facing pumping-station forebays. However, it should be emphasized that the recommended guide-wall deflection angle of $\theta = 25^\circ$ is not a universal value for all pumping-station forebays. The optimal guide-wall deflection angle may vary with forebay geometry, inflow discharge, sediment concentration, pump-unit operating combination, water level, and guide-wall position. In this study, the $\theta = 25^\circ$ scheme is considered the preferred overall scheme only under the present forebay layout, measured inlet velocity of 0.69 m/s, sediment-laden inflow condition, B# and C# pump operating combination, and selected guide-wall position. For other pumping stations or operating conditions, further numerical simulations, physical model tests, or field verification should be conducted before engineering application.

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