

Article

Study on Comparison of Energy Dissipation Measures for Retaining Weirs at the Outlet of Large-Scale Low-Lift Pumping Stations

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Abstract

In large-scale low-lift pumping stations, in order to adopt siphon outlet channels under the condition of no water in the outlet channel, a retaining weir needs to be set on the outlet side of the pumping station. To ensure the safe and stable operation of the retaining weir, the problem of energy dissipation of the retaining weir needs to be solved. Based on the VOF two-phase flow model, numerical simulations of three-dimensional turbulent flows were carried out for energy dissipation measures such as stilling basins, toe pier energy dissipation, suspended grid for energy dissipation, and their combinations, and the flow fields, hydraulic characteristics, and energy dissipation effects under different energy dissipation measures were compared. The research shows that the toe pier–suspended grid combined scheme can effectively break and weaken the large-scale vortices behind the retaining weir. Compared with the case of only using a stilling basin for energy dissipation, the maximum bottom velocity is reduced by 31%, and the maximum dissipation rate is increased by 119%. A comprehensive evaluation objective function is established with the relative bottom velocity and energy dissipation rate in the stilling basin as the quantification indexes. Through further analysis, the value of the toe pier–suspended grid combined scheme is the lowest, which is 37.84% lower than that of the traditional stilling basin, and the energy dissipation efficiency is the best. The toe pier–suspended grid combined scheme effectively optimizes flow conditions and improves energy dissipation, offering theoretical and engineering references for the energy dissipation design of retaining weirs in low-lift and large-flow pumping stations.

Keywords: low-lift pumping station; toe pier–suspended grid combined energy dissipator; retaining weir; two-phase flow; numerical simulation



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1. Introduction

With the economic development of China, large-scale low-lift pumping stations have been continuously constructed, which play a crucial role in key fields such as water resource allocation, urban flood control, and agricultural irrigation [1]. Due to its good hydraulic performance and reliable flow cutoff, the siphon outlet channel has been widely used in large-scale irrigation and drainage projects [2]. However, the application of the siphon

outlet channel has certain requirements for the water level of the outlet sump. In order to adopt the siphon outlet channel, some pumping station projects have set retaining weirs on the outlet side to raise the water level to meet the operation requirements. The installation of the retaining weir results in high-energy flow, posing a significant risk of damage to the outlet structures. Consequently, energy dissipators must be incorporated to ensure the safe and stable operation of the pumping station's outlet works.

Many scholars have carried out relevant research. Regarding the siphon outlet channel, the siphon formation process can be divided into the hydraulic air expulsion stage and the hydraulic air entrainment stage. In the hydraulic air expulsion stage, the initial air mass is discharged as a whole after being compressed. In the hydraulic air entrainment stage, the air exhaust mainly takes the form of bubble flow, accompanied by strong water–air mixing [3]. Rahim et al. [4] used the RNG k - ϵ turbulence model and the VOF model to calculate the discharge coefficient of the siphon outlet channel, and compared it with the model test. The data showed a high degree of consistency and good agreement, verifying the feasibility of numerical simulation. Aydin M.C. et al. [5] carried out ANSYS Fluent-based numerical simulation on the air entering the siphon during the drainage process, and also observed the air entrainment phenomenon in the physical model test. It was found that the air flow in the siphon would lead to a decrease in the drainage effect and vibration. Xu et al. [6] have found that there are significant eddies in the descending section of the siphon outlet channel, and a stable negative pressure is formed at the top of the hump section. Yang et al. [7] found that with the increase in the pump discharge, the uniformity of the axial velocity distribution in the siphon outlet channel is enhanced, while the eddy current intensity and the maximum pressure fluctuation in the hump section are both reduced. Houichi L. et al. [8] carried out physical tests on two siphon channels and determined their application ranges. Babaeian-Koopaei K. et al. [9] optimized the model of the spillway siphon channel in the design project. Zhu et al. [10] used Fluent-based numerical simulation methods to predict the internal flow field of the siphon outlet channel of large pumping stations and established an evaluation system for the hydraulic characteristics of the siphon outlet channel.

Regarding the energy dissipators in the stilling basin, the currently common auxiliary energy dissipation facilities include baffle piers, T-shaped piers, end sills, and suspended grids [11]. This type of structure enhances the turbulent mixing of the water body in the basin, changes the shape of the hydraulic jump, and increases the velocity gradient inside the water flow, thereby effectively improving the energy dissipation efficiency [12]. Serife et al. [13] studied the energy dissipation effect of the toe pier combined with four different shapes of baffle piers. The results showed that the stilling basin with toe piers and T-shaped piers had the best energy dissipation effect. Muhammad et al. [14] analyzed the influence of the wedge-shaped diversion pier on the underflow stilling basin based on the Flow3d software (<https://www.flow3d.com/>) and found that it could reduce the length of the hydraulic jump and increase the energy dissipation rate of the stilling basin. Khadka and Rai [15] reconstructed the flow field inside a hydropower station stilling basin with complex geometric configurations via CFD simulations, and verified that CFD serves as an effective tool for the design and retrofit of stilling basins. Macián-Pérez et al. [16] adopted CFD technology to conduct numerical simulations for six operating conditions of stepped stilling basins with adverse steps. Their study verified that the CFD method can accurately characterize hydraulic jump behaviors and effectively alleviate bed pressure fluctuations, offering a reliable means for the design optimization of adverse stepped stilling basins. Jiang et al. [17] carried out 75 groups of numerical tests on critical A-jumps in the practical engineering of high dams to systematically reveal the influences of incident angle and adverse step height on the conjugate water depth ratio, roller length, and energy dissipation

rate of hydraulic jumps. Dahal et al. [18] conducted numerical simulations on the stilling basin of the Fewa Hydropower Project using Flow-3D. They systematically compared the energy dissipation performance of eight layout schemes for baffle blocks and chute blocks, and verified that honeycomb-structured energy dissipators induce intense turbulent dispersion via labyrinth flow channels. Wang et al. [19] compared the energy dissipation effects of trapezoidal piers with different layout forms. The results showed that when three rows of trapezoidal piers were arranged, the flow velocity could be significantly reduced and the energy dissipation rate could be increased, but the deceleration ratio was inversely proportional to the row spacing. Sun et al. [20] revealed the large-scale turbulence and strong water–air mixing effect formed under different working conditions by comparing the flow characteristics of two different forms of suspended grating energy dissipators under different working conditions. At the same time, some scholars have also studied new combined ways of auxiliary energy dissipators such as contraction pier + drop weir, T-shaped pier + tail weir, toe pier + suspended grid, and baffle piers + suspended grid. Liu et al. [21] found that the T-shaped pier with an erosion control plate can increase the water depth in the stilling basin and improve the energy dissipation effect. Zhou et al. [22] found that the toe pier–suspended grid combined energy dissipator improved the flow pattern in the stilling basin, and the overall vorticity distribution in the basin was more uniform and produces a superposition of beneficial effects.

Nevertheless, existing studies mainly concentrate on the geometric configuration of energy dissipators or the energy dissipation performance of combined dissipators arranged inside conventional stilling basins, with few investigations focusing on combined energy dissipators installed downstream of retaining weirs in the siphon outlet conduits of pumping stations. To satisfy the operational requirements of siphon outlet conduits, retaining weirs are commonly arranged in the outlet pools of numerous large pumping stations, which inevitably brings about the problem of energy dissipation downstream of the weirs. Such working conditions are characterized by large discharge, high incoming flow velocity, and intensive vortex formation. Differences in research subjects and inflow conditions will lead to variant energy dissipation efficiencies of dissipator structures, making existing research results inapplicable to this scenario. Accordingly, this paper carries out targeted research on this issue. Systematic analysis is conducted on the energy dissipation calculation results of traditional stilling basins, stilling basins with toe piers as single auxiliary energy dissipators, stilling basins with suspended grids, and stilling basins adopting the toe pier–suspended grid combined energy dissipator. Analyses are carried out from the perspectives of vorticity, flow velocity, and dissipation rate, and the best-performing scheme is determined based on the comprehensive evaluation objective function. The findings provide theoretical support for the safe and stable operation of outlet structures arranged behind the weir of siphon outlet channels under complex working conditions.

2. Research Model

2.1. Computational Model and Parameters

The outlet sump with a water-retaining weir as part of the pumping station is taken as the research object. The designed single-pump discharge of this pumping station is $47.25 \text{ m}^3/\text{s}$, the lowest operating water level (LOWL) of the outlet channel is 79.02 m, and the designed operating water level (DOWL) is 80.5 m. The computational domain of the numerical simulation includes the siphon outlet channel and the outlet sump with a water-retaining weir. The single-line diagram of the computational area is shown in Figure 1, and the three-dimensional modeling diagram is shown in Figure 2.

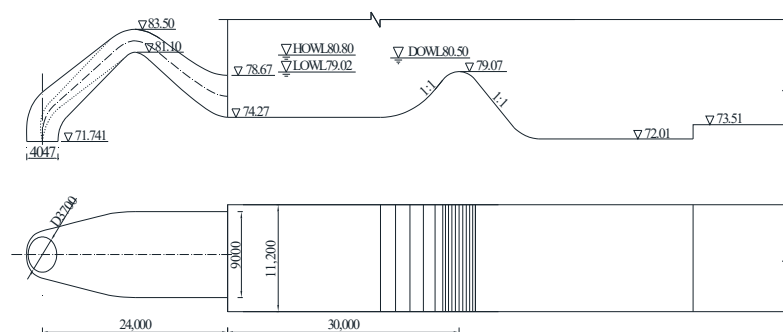


Figure 1. Single-line diagram of the computational area.

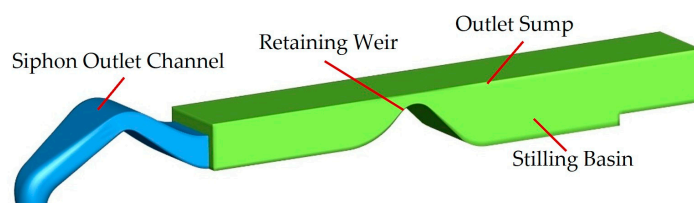


Figure 2. Three-dimensional model.

2.2. Design of Energy Dissipation Scheme Behind the Retaining Weir

During the energy dissipation process, if the energy dissipation effect behind the retaining weir is not ideal and the velocity of the discharged water flow is less than 18 m/s, auxiliary energy dissipators such as toe piers, stilling basins, suspended grids, and baffle piers can be set in the stilling basin [23]. Auxiliary energy dissipators can strengthen the dispersion, mutual impact, and friction of the water flow, reduce the scouring damage of the water flow to the hydraulic structure after the hydraulic jump, and make the energy dissipation structure more reasonable, economical, and effective.

The best-performing scheme of the energy dissipator behind the weir is selected by analyzing and comparing the flow characteristics of various energy dissipation schemes. Therefore, four schemes of the energy dissipator behind the retaining weir are proposed, namely Scheme F1: energy dissipation by the stilling basin; Scheme F2: combined energy dissipation by the stilling basin and toe piers; Scheme F3: combined energy dissipation by the stilling basin and suspended grids; Scheme F4: combined energy dissipation by the stilling basin, toe piers, and suspended grids, as shown in Table 1.

Table 1. Schemes of energy dissipators.

Scheme	Stilling Basin	Toe Pier	Suspended Grid
F1	✓		
F2	✓	✓	
F3	✓		✓
F4	✓	✓	✓

Note: "✓" indicates that the corresponding energy dissipator is adopted.

The single-line diagram of the outlet sump under different energy dissipation schemes is shown in Figure 3. The perspective view of the outlet sump is shown in Figure 4. Scheme F1 only uses the stilling basin for energy dissipation. Unstructured grids are used, and local encryption is carried out on the bottom of the retaining weir and the bottom of the stilling basin behind the retaining weir. Scheme F2 uses the stilling basin + toe piers for energy dissipation. The toe piers are arranged at the inlet of the stilling basin, with a pier width of 800 mm, a pier length of 2293 mm, and a spacing of 2200 mm between adjacent toe piers. Scheme F3 is a layout scheme that uses the stilling basin + suspended grids for energy

dissipation. The suspended grids start to be arranged at the front end of the stilling basin. When the cross-sectional shape of the grid bars is rectangular, the water-blocking effect is the best. And when the height of the grid bar position is the same as the bottom elevation of the channel behind the basin, the energy dissipation effect of the stilling basin is the best. Therefore, rectangular grid bars with a cross-sectional size of 350 mm $\times$ 350 mm are selected, and the spacing between adjacent suspended grids is 750 mm, and a total of 13 are arranged at equal intervals [24]. Scheme F4 uses the stilling basin + toe piers + suspended grids for energy dissipation. The toe piers start to be arranged at the front end of the stilling basin, and the suspended grids are arranged above the toe piers. The pier width is 800 mm, the pier length is 2293 mm, the spacing between adjacent toe piers is 2200 mm, and rectangular grid bars with a cross-sectional dimension of 350 mm $\times$ 350 mm, are arranged in series and equidistantly in the stilling basin. The spacing between adjacent suspended grids is 750 mm, and a total of 13 are arranged.

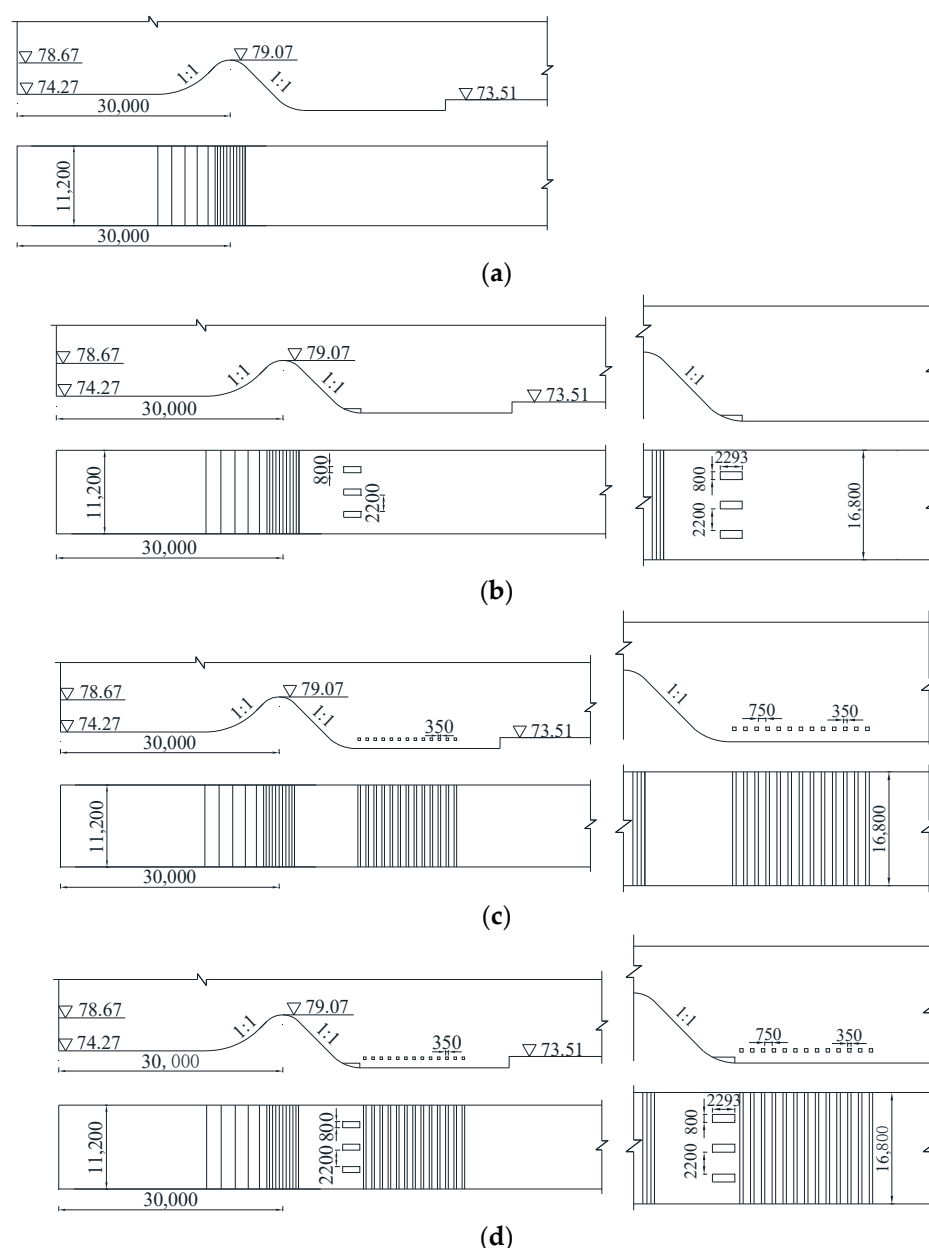


Figure 3. Single-line diagram of the outlet sump for different energy dissipation schemes (unit of dimension: mm, unit of elevation: m). (a) F1; (b) F2; (c) F3; (d) F4.

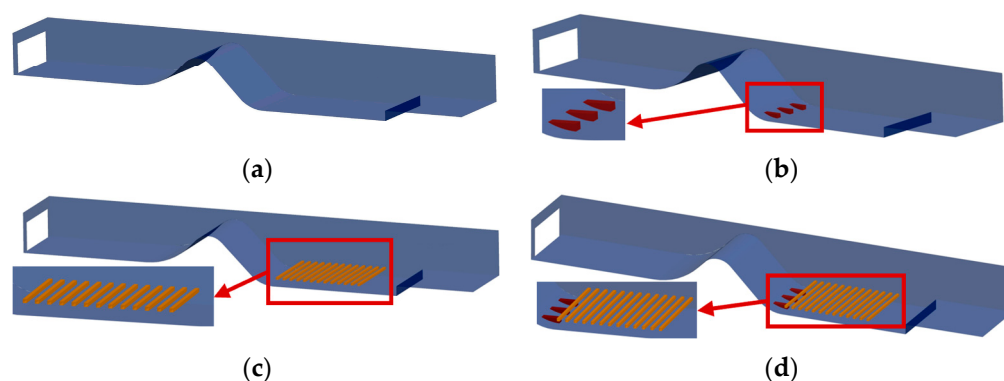


Figure 4. Perspective view of the outlet pool for different energy dissipation schemes. (a) F1; (b) F2; (c) F3; (d) F4.

3. Mathematical Model

3.1. Governing Equations

The computational domain is numerically simulated based on the VOF two-phase flow model. By solving the continuity equations of the volume fractions of water and air, the interface between the gas–liquid two phases is tracked, thereby detecting the changes in the gas–liquid two-phase flow. The maximum flow velocity within the computational domain reaches 12.8 m/s. The compressibility effect of water is evaluated using the Mach number Ma , defined as the ratio of the characteristic flow velocity u to the acoustic velocity c in water. The calculated Mach number $Ma = u/c = 12.8/1480 \approx 0.0086$, which is far lower than the general criterion of $Ma < 0.3$ for incompressible flow [25]. This result indicates that variations in water density induced by pressure fluctuations during flow are negligible. Accordingly, the flow field in the computational domain can be simplified as three-dimensional incompressible inviscid turbulent flow. The governing equations for numerical calculation are

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \quad (1)$$

Momentum equation

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (2)$$

Volume fraction equation

$$\frac{\partial \alpha_1}{\partial t} + \mathbf{u} \cdot \nabla \alpha_1 = 0 \quad (3)$$

$$\frac{\partial \alpha_2}{\partial t} + \mathbf{u} \cdot \nabla \alpha_2 = 0 \quad (4)$$

Within a grid control volume, the expression for the phase-dependent material properties is

$$\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2 \quad (5)$$

$$\mu = \alpha_1 \mu_1 + \alpha_2 \mu_2 \quad (6)$$

where the subscript 1 represents the liquid phase, and subscript 2 represents the gas phase; u_j is the velocity component parallel to the coordinate axis x_j , ($j = 1, 2, 3 \dots$); u_i is the velocity component parallel to the coordinate axis x_i , ($i = 1, 2, 3 \dots$); f_i is the body force acting on a unit mass of fluid; p is the pressure on the fluid microelement; α_1 and α_2 are the volume

fractions of water and air respectively, $\alpha_1 + \alpha_2 = 1$; ρ is the density; ∇ is the Hamiltonian operator; μ is the dynamic viscosity coefficient; t is the time; $\mathbf{u}$ is the velocity vector.

3.2. Turbulence Model

The RNG k - ε turbulence model is adopted. Based on the standard k - ε turbulence model, this model considers the rotation in the mean flow and the case of rotational flow by modifying the turbulent viscosity. Therefore, the RNG k - ε turbulence model has good adaptability to transient flow fields with typical strong swirl characteristics [26].

k equation

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \rho \varepsilon \quad (7)$$

ε equation

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{C_{1\varepsilon}}{k} \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{K} - R \quad (8)$$

where k is the turbulent kinetic energy; ε is the dissipation rate; the effective turbulent viscosity coefficient $\mu_{eff} = \mu + \mu_t$, α_k and α_ε is the effective Prandtl number, for high Reynolds number flows, $\alpha_k = \alpha_\varepsilon \approx 1.39$.

The RNG turbulence model and the VOF multiphase flow model can be coupled to simulate the gas–liquid two-phase motion in the siphon channel and the stilling basin behind the retaining weir. Water is the main phase and gas is the second phase. The VOF model is used to reflect the dynamic process of the water–air interface in the stilling basin, and the RNG model is applicable to the process of water flow impacting the stilling basin.

3.3. Mesh Independence Analysis and Solution Settings

The computational domain involves air and water. An air domain with a certain height needs to be set above the outlet sump, and the water level height of the outlet sump is consistent with the lowest operating water level. Since it is necessary to ensure the uniformity of the water inflow and the stability of the outflow, an extension section needs to be added at the inlet of the outlet channel and the rear end of the outlet sump respectively. The inlet extension is twice the inlet diameter, and the rear end of the outlet sump extends 50 m.

For the computational domain, structured grids are used to divide the siphon outlet channel, inlet extension section, outlet extension section, and gas domain with relatively simple structures, while unstructured grids are used to divide the outlet basin with a water-retaining weir.

Five sets of qualified meshing schemes with different grid quantities are established to investigate the influence of grid number on numerical results. All simulations are carried out under identical boundary conditions and solver settings. Taking Scheme F4 as an example, the energy dissipation rate E and maximum near-bottom flow velocity $v_{\max}$ are selected as evaluation indicators, and the calculated results are listed in Table 2.

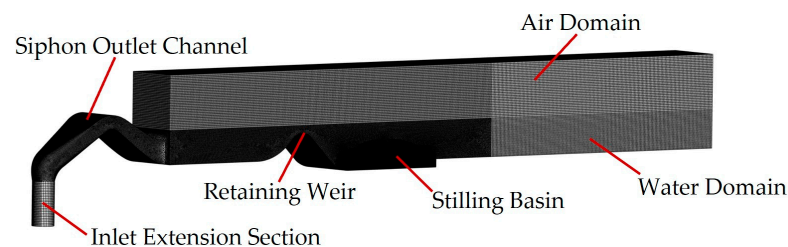
Table 2. Grid independence test.

Scheme	Total Grid Number ($\times 10^6$)	$v_{\max}$ (m/s)	E (%)
G1	1.1	6.42	70.56
G2	1.8	6.24	71.82
G3	2.5	6.15	72.31
G4	3.2	6.10	72.73
G5	3.8	6.08	72.84

It can be seen from the results that after the total grid number reaches 3.2×10^6 , the relative change rates of the two indicators are both less than 1.5% with further grid refinement. The numerical uncertainties of $v_{\max}$ and E calculated via the Grid Convergence Index (GCI) method [27] are 1.3% and 1.2%, which is lower than the acceptable threshold of 2% for hydraulic numerical simulations [28]. Accordingly, the mesh with approximately 3.2×10^6 cells is adopted for subsequent simulations of Scheme F4.

To quantitatively evaluate the capability of the mesh near the suspended grid to capture flow separation and vortex shedding, the dimensionless criterion $\Delta x/D$ is adopted for assessment. The suspended grid consists of rectangular bars with a cross-section of 350 mm $\times$ 350 mm. Boundary layer separation, shear layer rolling-up, and periodic vortex shedding in the wake occur when water flows past the bars, and these physical processes impose stringent requirements on mesh resolution. Δx denotes the characteristic mesh size after local mesh refinement around the suspended grid, while $D = 0.35$ m stands for the bar width. In this study, the mesh in the suspended grid zone is locally refined to $\Delta x = 1.5$ cm, yielding $\Delta x/D \approx 0.043$. This dimensionless resolution matches the recommended spanwise resolution values reported in large eddy simulation studies on flow around square cylinders [29], demonstrating that the adopted mesh size is sufficient to resolve local flow separation and vortex shedding.

After grid independence verification, for Scheme F1, the bottom behind the weir and the bottom of the stilling basin are locally refined, and a total of 2,187,008 grid cells are divided in the computational domain; for Scheme F2, the bottom behind the weir, the toe pier, and the bottom of the stilling basin are locally refined, and a total of 2,209,036 grid cells are divided; for Scheme F3, the bottom behind the weir, the suspended grid, and the bottom of the stilling basin are locally refined, and a total of 2,208,744 grid cells are divided; for Scheme F4, the bottom behind the weir, the suspended grid, and the bottom of the stilling basin are locally refined, and a total of 3,206,995 grid cells are divided. Taking Scheme F4 as an example, the grid division diagram is shown in Figure 5.

**Figure 5.** Grid division diagram.

The Fluent software (<https://www.ansys.com/>) is used to perform transient numerical calculations on the computational domain. The inlet velocity of the model is $v_{in} = 3.67$ m/s. The control equations are discretized using the finite volume method (FVM). In the numerical solution, an implicit algorithm is used to handle the volume fraction equation, and the PISO algorithm is used to iteratively solve the pressure–velocity coupling. The computation is regarded as converged when the iterative residual curve falls below the

preset threshold of 1×10^{-4} and the relative error of inlet and outlet discharge is less than 1%. For the initial conditions, the region below the designed water level of the inlet basin is set as the water phase (volume fraction 1), and the rest of the region is the gas phase (volume fraction 0). The atmospheric outlet above the water surface of the outlet basin adopts the pressure outlet boundary condition, and the relative pressure value is 0. The no-slip assumption is adopted for the entire computational domain.

To eliminate the effect of temporal discretization on simulation outputs, three typical time steps $\Delta t_1 = 0.01$ s, $\Delta t_2 = 0.005$ s and $\Delta t_3 = 0.002$ s were examined under the baseline working condition of design discharge and minimum operating water level. The maximum near-bottom flow velocity $v_{\max}$ was adopted as the evaluation index. The relative error of $v_{\max}$ between Δt_2 and Δt_3 was calculated to be 0.16%. Consequently, a time step of 0.005 s was selected to resolve the transient evolution of the gas–liquid interface. All simulation cases in this study were performed under a 16-core parallel computing environment. The average computation time for transient simulations with a total physical time of 150 s for each working condition was approximately 72 h.

3.4. Validation of the Effectiveness of Numerical Calculations

To verify the reliability of the turbulence model and numerical settings adopted for energy dissipation calculation in the outlet pool, a full-scale (1:1) CFD numerical model was established corresponding to the physical experimental model documented in Reference [30]. The physical photograph and single-line diagram of this model are presented in Figure 6, and numerical configurations were implemented in accordance with the experimental parameters provided in the literature.

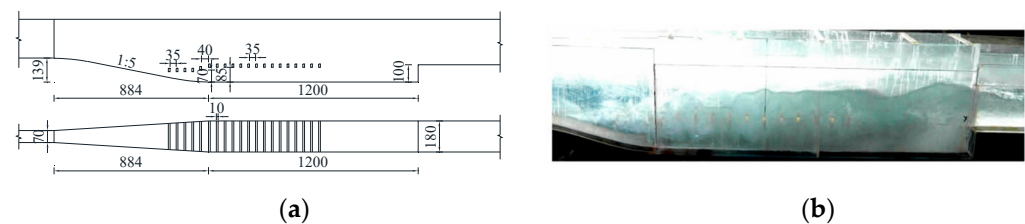


Figure 6. Single-line diagram of the outlet sump for model test. (a) Single-line diagram; (b) physical photograph [30].

The numerically calculated energy dissipation rate and maximum water depth at each section were extracted and compared with the experimental data from the cited literature, and the comparison results are listed in Table 3. The maximum relative error between numerical simulation results and model test data is less than 3%. It verifies the reliability of the numerical simulation method adopted in this paper, which can serve as a fundamental tool for the research on energy dissipation calculation of the outlet sump.

Table 3. Comparison of the results between model test and numerical calculation.

Scheme	Maximum Water Depth (cm)			Energy Dissipation Rate (%)		
	Model Test	Numerical Simulation	Error	Model Test	Numerical Simulation	Error
1	31.40	32.21	2.6%	74.29	75.36	1.4%
2	26.40	27.15	2.8%	76.07	77.34	1.7%
3	27.65	27.25	−1.4%	76.28	77.49	1.6%
4	28.02	28.43	1.5%	76.44	77.57	1.5%

4. Calculation Results and Analysis

4.1. Analysis of the Energy Dissipation Process of Different Energy Dissipators

To more carefully analyze the energy dissipation of different energy dissipators when the pump station starts up and there is no water in the outlet sump, from the moment the water flow crosses the top of the water-retaining weir and starts to discharge until the energy dissipation is completed, a three-dimensional energy dissipation process diagram of the outlet sump was created. The free surface process diagram of the energy dissipation behind the retaining weir of the stilling basin is shown in Figure 7.

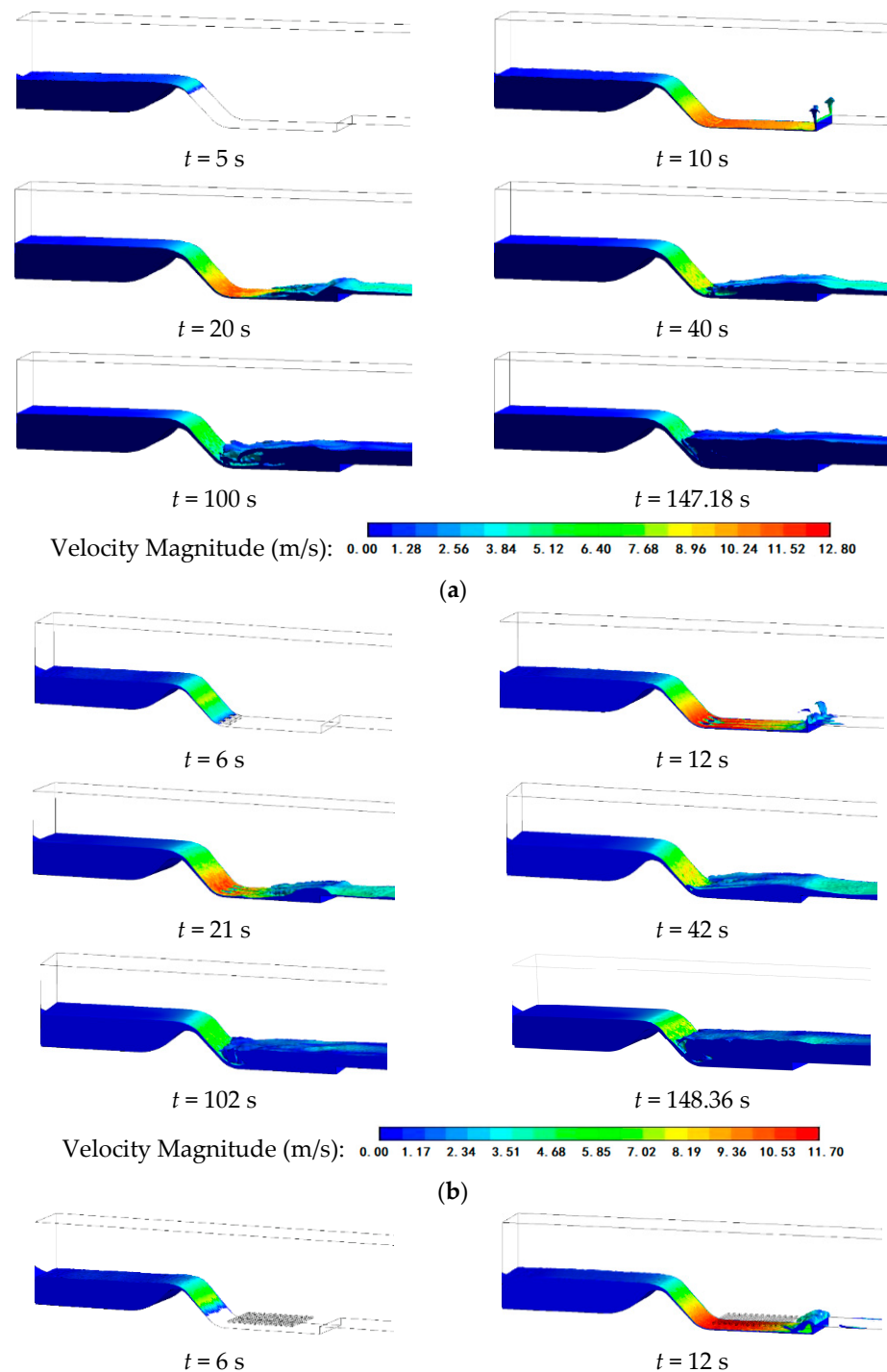


Figure 7. Cont.

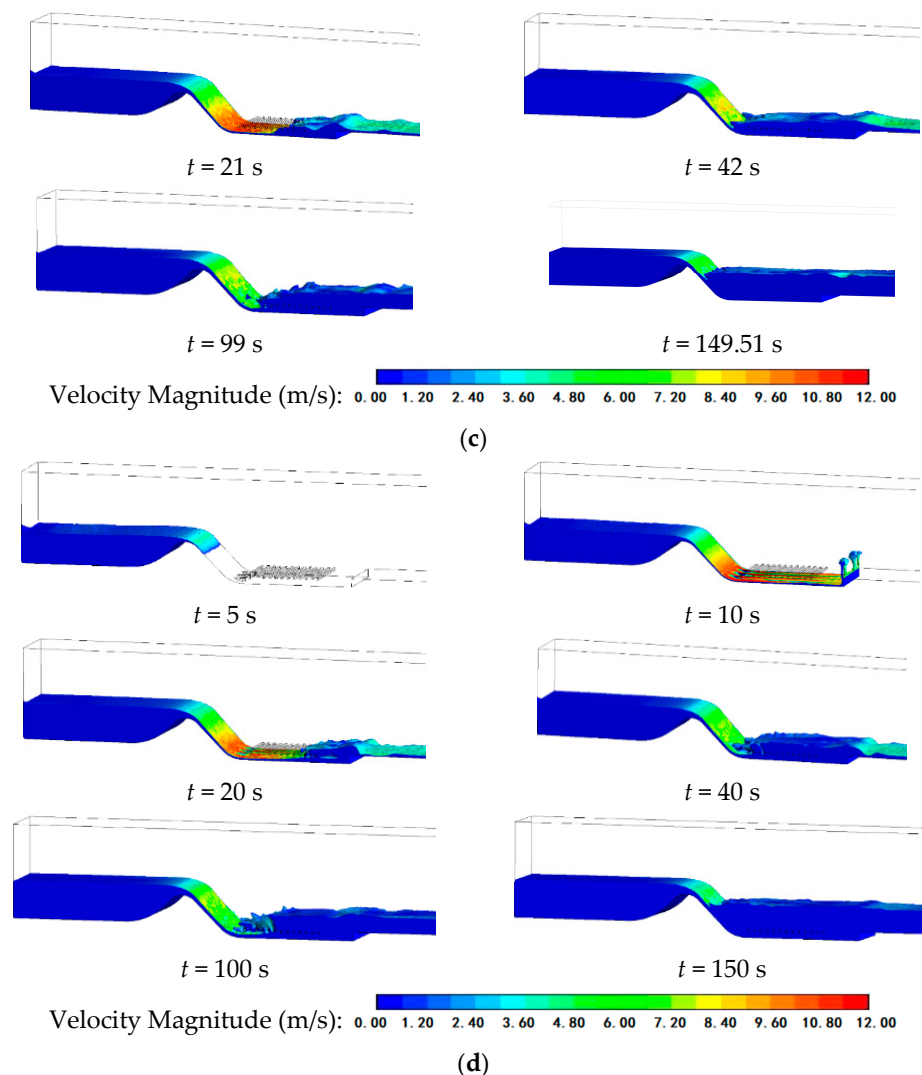


Figure 7. Free surface process diagram of the energy dissipation behind the retaining weir of the outlet sump. (a) F1; (b) F2; (c) F3; (d) F4.

During the energy dissipation process, the initial water flow velocity of each scheme is very high, presenting a rapid flow state. The water flow directly impacts the end sill of the stilling basin and then leaps up. In the middle stage, after the upstream inflow enters the stilling basin, it entrains bubbles. Since the tail water level is lower than the conjugate depth after the jump, an obvious repelled downstream hydraulic jump is formed. When the discharged water flow transitions from a rapid flow state to a slow flow state, a hydraulic jump occurs. The water flow entraps air and passes through the air–water interface, causing a large number of bubbles in the hydraulic jump section to be retained in the water flow, carried away as the water flow moves, and finally exchanged back to the free liquid surface and discharged. Eventually, the free liquid surface in the stilling basin stabilizes, the flow velocity decreases, and the air entrainment weakens.

F1 has no auxiliary structure and forms a repelled downstream hydraulic jump. The initial flow velocity is the largest, and the maximum flow velocity can reach 12.8 m/s; for F2, the incoming water flow into the basin is dispersed into multiple small-scale water flows by the toe piers. The toe piers play a role in blocking the water flow and diverting it. The water flows passing through the toe piers impact and collide with each other, thus increasing the water depth at the head of the basin. The flow velocity of the free liquid surface of the discharged water flow is very high, and the maximum flow velocity reaches

11.7 m/s, but it is smaller than that of F1 during the same period; F3 uses a suspended grid to enhance shear. A part of the trajectory of the upper-layer water body in the stilling basin at the first suspended grid in the upper layer rolls around the grid, forming a backflow that intensifies the shear and collision of the water body. A part smoothly transitions to the downstream above the suspended grid, and another part rapidly flows through the gap between the suspended grid and the floor. Through the blocking and diverting effects of the suspended grid, the water depth at the head of the stilling basin is increased. Since there are no toe piers arranged, the initial maximum flow velocity is 12 m/s, which is increased compared with scheme F2; F4 combines toe piers and a suspended grid. The incoming water flow into the basin undergoes diversion and flushing effects by the toe piers, and the water body becomes turbulent at the head of the basin. Then, through the flow-stabilizing effect of the suspended grid, the water flow in the stilling basin makes a movement around the grid, and the overall flow pattern is good. The maximum flow velocity of the free liquid surface is 12 m/s.

By comparing the hydraulic jump length of each scheme at $t = 20$ s, it can be found that the hydraulic jump lengths of the four schemes are 16.0 m, 9.5 m, 15.6 m, and 9.2 m, revealing distinct differences in the flow confinement effect of different energy dissipators. In the cases without energy dissipators and with suspended grids alone, the hydraulic jump lengths reach 16.0 m and 15.6 m, which remain relatively large.

Scheme F1 is not equipped with auxiliary energy dissipators and cannot reduce the flow kinetic energy at the initial stage of water discharge. The flow travels a long distance inside the stilling basin before the formation of a hydraulic jump. For Scheme F2, the formation of reverse recirculation behind the toe piers pushes the hydraulic jump significantly upstream. The reduction in hydraulic jump length for Scheme F3 is insignificant. The mainstream downstream of the weir falls at high velocity along the basin floor, while the suspended grids are arranged in the upper part of the stilling basin and cannot directly interact with and disturb the core mainstream. At $t = 20$ s, the grids only exert weak shear on the upper slow flow, resulting in an extremely limited capacity to regulate the hydraulic jump pattern. Scheme F4 adopts combined toe piers and suspended grids, achieving a further reduction in hydraulic jump length compared with Scheme F2. The toe piers enlarge the contact shear area with the flow, and the suspended grids impose frictional resistance and flow-cutting effects. The synergistic effect of both structures enables the flow to complete kinetic energy dissipation and potential energy conversion over a shorter distance. Its hydraulic jump length is reduced by approximately 42.5% relative to Scheme F1, demonstrating that the combined energy dissipator can effectively shrink the hydraulic jump region and optimize the pressure distribution within the stilling basin.

Apart from differences in flow pattern and flow velocity, the stabilization time of the free surface also varies among different schemes. The stabilization time is defined as the duration from the moment water starts to overtop the retaining weir until the free surface downstream of the stilling basin reaches a steady state. The stabilization durations for the four schemes are 147.18 s, 148.36 s, 149.51 s, and 150 s, with insignificant overall discrepancies. Regardless of the type of energy dissipator, after flowing over the weir crest, the water undergoes a complete sequence of physical processes: impacting the stilling basin floor, raising the water level inside the basin, forming a stable hydraulic jump, and attaining the design downstream water level. The timescale of this process is governed by global boundary conditions including design discharge, design water level, and stilling basin volume, and is not remarkably affected by modifications to local energy dissipators.

The longer stabilization time observed in Scheme F4 does not indicate insufficient energy dissipation performance; instead, it is an inevitable outcome of intense turbulence in the early stage. Equipped with combined toe piers and suspended grids, Scheme F4

provides a larger contact area with the flow and imposes greater frictional resistance, enabling more thorough energy dissipation. Although an earlier stabilization of the water level in the outlet pool implies a more controllable energy dissipation process and allows the required inflow to be supplied to the downstream region sooner, for energy dissipation schemes with minor differences in stabilization time, the energy dissipation rate and near-bed flow velocity are more critical indicators for the stable and safe operation of pumping stations.

4.2. Analysis of the Hydraulic Performance of the Stilling Basin

In the case of using a stilling basin, adding a suitable auxiliary energy dissipator device can effectively improve the flow pattern of the discharged water flow behind the retaining weir. Therefore, a reasonable energy dissipation layout scheme has an important impact on the energy dissipation effect behind the retaining weir. The following will focus on analyzing the distribution of vortex structures, the near-bottom velocity, and the dissipation rate of each energy dissipation scheme and make comparisons.

The Omega criterion [31] is adopted to identify vortex structures of the flow downstream of the weir, and the swirling strength λ_{ci} is used for iso-surface rendering. The definition of the core identification parameter Omega is as follows [31,32]:

$$\Omega = \frac{\|\omega\|_F^2}{\|D\|_F^2 + \|\omega\|_F^2 + \varepsilon} \quad (9)$$

where $\|\omega\|_F$ and $\|D\|_F$ denote the Frobenius norms of the rotation tensor and strain-rate tensor, and ε represents a small positive constant.

λ_{ci} characterizes the rotational intensity of flow, defined as [33]

$$\lambda_{ci} = \frac{\sqrt{3}}{2} \left(\sqrt[3]{\Delta - \frac{1}{2}R} + \sqrt[3]{\Delta + \frac{1}{2}R} \right) \quad (10)$$

where Δ is the discriminant of the eigenvalue equation for the velocity gradient tensor, and R refers to the third invariant of the velocity gradient tensor.

The Omega criterion with $\Omega = 0.52$ [31] is applied to identify vortices within the outlet conduit, accompanied by color rendering based on swirling strength. The vortex structures inside the stilling basin under various schemes are presented in Figure 8.

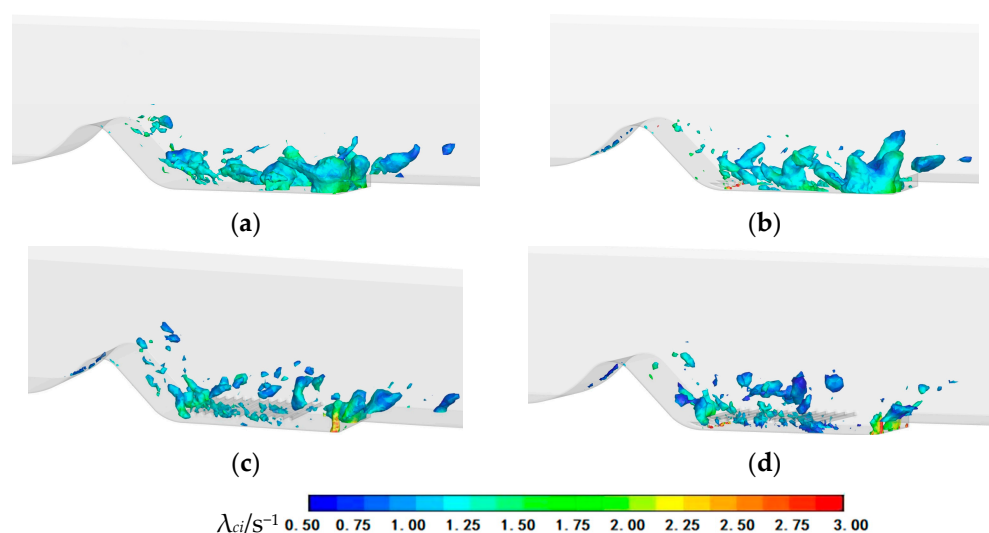


Figure 8. Distribution diagrams of vortex structures behind the weir under different energy dissipation schemes. (a) F1; (b) F2; (c) F3; (d) F4.

In Scheme F1, large-scale recirculation rolls emerge from the middle section of the stilling basin to the basin end sill, generating prominent vortex structures with large spatial dimensions and swirling strength concentrated at approximately 1.25 s^{-1} . This phenomenon arises because the discharged flow enters the stilling basin without being blocked by auxiliary energy dissipators, triggering a distant hydraulic jump. The bulk flow retains considerable kinetic energy and propagates toward the outlet channel.

For Scheme F2, the installation of toe piers splits the inflow into the stilling basin and deflects the main flow away from the basin floor. Compared with Scheme F1, the vortex dimension near the outflow section downstream of the weir declines, whereas large-scale vortices still persist from the basin midsection to the end sill. Smaller vortices with elevated swirling strength are generated at the rear of the toe piers.

In Scheme F3, the suspended grid dissipator breaks up the inherent large-scale vortices inside the stilling basin. Small vortices formed behind the grid intensify mixing and collision of ambient water masses, improving internal energy dissipation and alleviating water surface fluctuations. The size of vortices at the basin end sill is further reduced, and small-scale vortices with swirling strength ranging from 2.25 s^{-1} to 3.00 s^{-1} develop along the sidewalls.

Scheme F4 adopts the combined arrangement of toe piers and suspended grids, which strengthens fluid shearing and impingement within the hydraulic jump zone. After flow discharges from the retaining weir into the basin, the vortex size at the inflow section is further lowered, and the overall swirling strength is relatively low, mainly distributed between 0.50 s^{-1} and 1.25 s^{-1} . Numerous small-scale vortices form around the suspended grids, disintegrating the original large vortices in the basin and shrinking the vortex scale near the end sill. Nevertheless, small-scale vortices with strong rotational intensity remain distributed along the sidewalls.

To further analyze the distribution state of the near-bottom velocity in the stilling basin behind the water-retaining weir, the near-bottom flow velocity distribution in the stilling basin behind the retaining weir under different schemes is formed, as shown in Figure 9. The energy dissipation effect of Scheme F1 is poor, and the maximum velocity of flow on the inlet floor slab reaches 8.0 m/s , and the water flow deflects towards both sides of the floor slab. The velocities on both sides are relatively large, concentrated in distribution, and the water flow velocity in the middle part of the stilling basin changes uniformly; Scheme F2 has a significant effect on reducing the water flow velocity entering the basin. The toe piers disperse the discharged water flow into multiple small water flows, and the water flows collide and impact with each other, thus raising the water depth at the head of the stilling basin. The maximum near-bottom velocity of the water flow entering the basin is 7.2 m/s . The toe piers' auxiliary energy dissipator has a good inhibitory effect on reducing the near-bottom velocity of the discharged water flow. Under the diversion and flow-deflection effects of the toe piers, the discharged water flow is in a state of longitudinal extension, lateral contraction, and mainstream dispersion. The overall bottom velocity of the stilling basin in Scheme F3 changes uniformly. The water flow entering the basin increases the water depth at the head of the basin through the blocking and diversion effects of the suspended grids, but the water flow passes through the gap between the suspended grids and the bottom slab of the stilling basin rapidly. The maximum near-bottom velocity of the water flow entering the basin is 7.4 m/s . Under the dispersion and flow-deflection effects of the suspended grids, the water flow entering the basin is in a state of mainstream dispersion, thus intensifying the shear collision between the main water flows in the basin and reducing the impact of the main water flow on the floor slab of the stilling basin. For the stilling basin with toe piers and suspended grid auxiliary energy dissipators in Scheme F4, the overall near-bottom velocity changes uniformly. The discharged water flow

increases the internal velocity gradient of the water flow behind the toe piers under the diversion and flow-deflection effects of the toe piers, and then further reduces the kinetic energy of the water flow through the blocking and diversion effects of the suspended grids. The water flow passes through the gap between the suspended grids and the floor slab of the stilling basin rapidly. The maximum near-bottom velocity of the water flow entering the basin is 6.1 m/s.

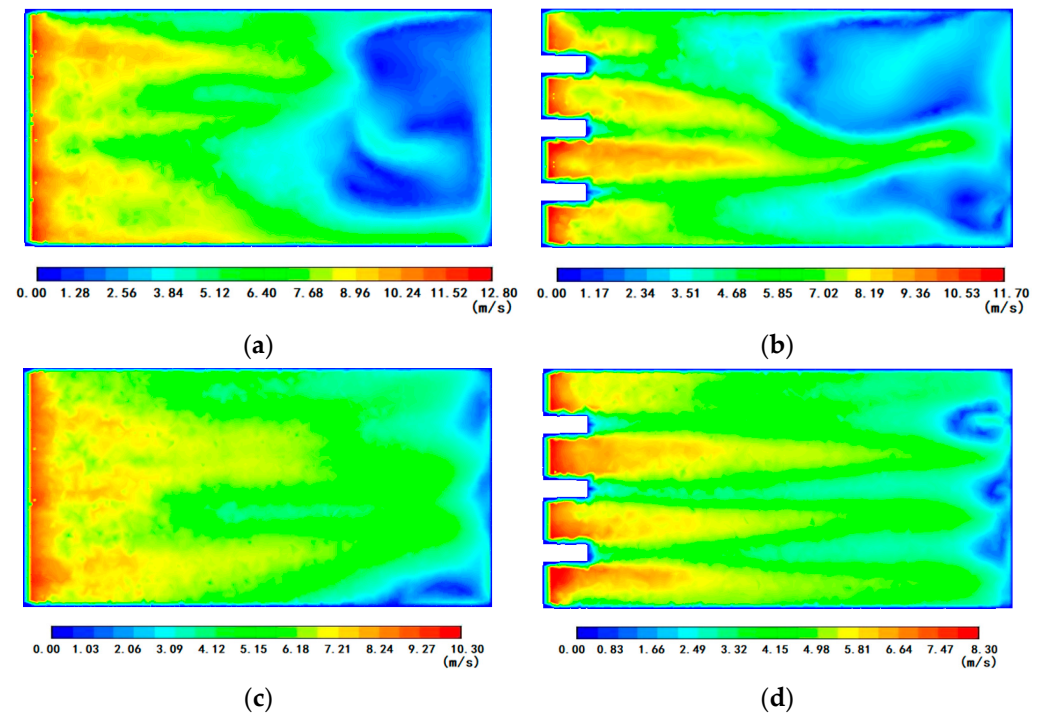


Figure 9. Contour map of the near-bottom velocity distribution in the stilling basin under different energy dissipators. (a) F1; (b) F2; (c) F3; (d) F4.

The dissipation rate refers to the rate at which turbulent kinetic energy is converted into molecular thermal kinetic energy under the action of molecular viscosity, and it is an important index for evaluating the energy dissipation effect. As the value of the dissipation rate increases, the energy loss of the water flow also increases. The distribution diagram of the near-bottom dissipation rate of the stilling basin plane behind the retaining weir under different energy dissipation schemes is shown in Figure 10. For Scheme F1, the kinetic energy dissipation is small, and the maximum value is located at the place where the discharged water flow at the front end of the stilling basin impacts the bottom of the stilling basin, with the maximum value being approximately $5.8 \text{ m}^2/\text{s}^3$. For scheme F2, the discharged water flow is in a state of longitudinal extension, lateral contraction, and mainstream dispersion. The water flow in the basin undergoes intense shearing, friction, and collision effects on both sides and behind the toe piers, with a relatively large dissipation rate, with the maximum being approximately $11.6 \text{ m}^2/\text{s}^3$. For scheme F3, under the action of the flow obstruction and diversion of the suspended grids, the water flow in the basin undergoes intense shearing, friction, and collision effects around the suspended grids, with a relatively large dissipation rate, with the maximum being approximately $9.7 \text{ m}^2/\text{s}^3$. For scheme F4, the incoming water flow is first diverted and deflected by the toe piers and is dispersed into multiple small water flows. Then, under the action of the flow obstruction and diversion of the suspended grids, a part of it rolls around the grids, forming a backflow that intensifies the shear and collision of the water body. The water flow in the basin undergoes intense shearing, friction, and collision effects around the toe

piers and the suspended grids, and the energy dissipation rate is relatively large, with the maximum being approximately $12.7 \text{ m}^2/\text{s}^3$.

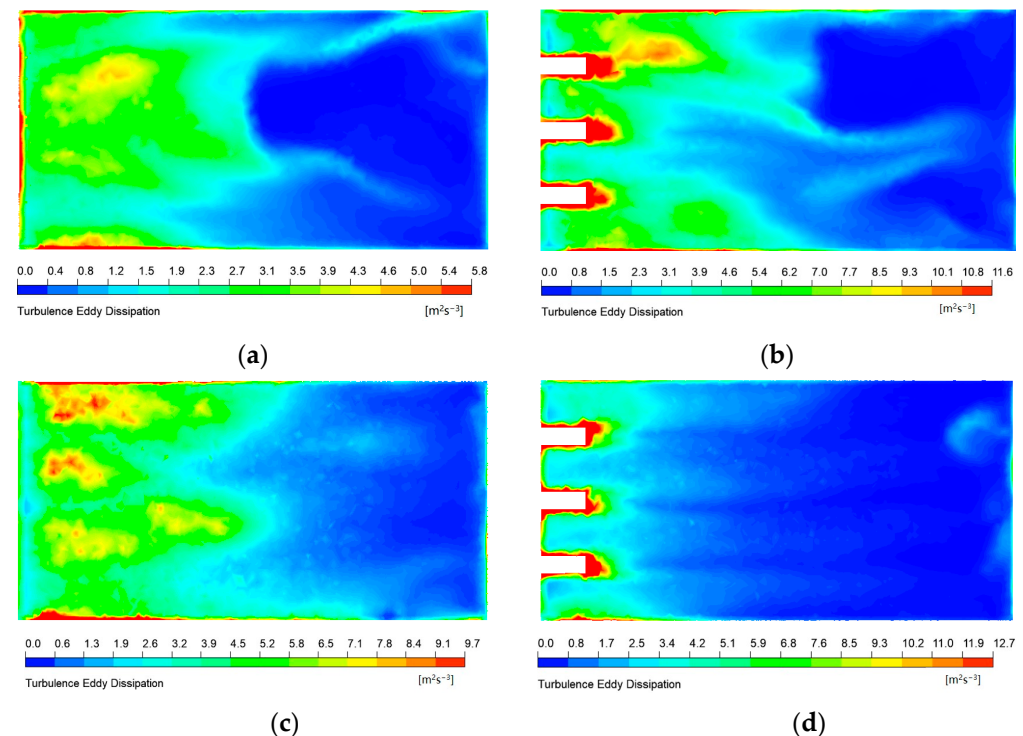


Figure 10. Contour map of the bottom dissipation rate distribution of the stilling basin under different energy dissipators. (a) F1; (b) F2; (c) F3; (d) F4.

Based on the above calculation results, the combined toe pier–suspended grid energy dissipator of Scheme F4 achieves great energy dissipation performance under this working condition. The mechanisms underlying the enhanced energy dissipation are elaborated as follows.

The first mechanism is the flow-splitting and jet-deflecting effect of toe piers. Installed at the inlet of the stilling basin, toe piers split the single high-speed mainstream discharged from the retaining weir into multiple narrow jets [34]. This process expands the area of shear layers and increases the contact perimeter between the multiple jets and surrounding low-velocity water, thereby raising the production term of turbulent kinetic energy. Meanwhile, the piers deflect the mainstream away from the basin floor to mitigate floor impact and reduce the time-averaged hydrodynamic pressure on the bottom plate.

Second, suspended grids span the upper zone of the stilling basin and force the high-speed upper flow to bypass the grid bars and turn downward. Water flows through both the upper and lower sides of the bars, where the grids exert three effects on the flow: frictional resistance, flow blocking, and flow cutting. The two separated streams recombine and collide after passing through the grids, dissipating energy continuously. Small-scale vortices shed from the trailing edges of grid bars featuring high strain rates, which rapidly convert turbulent kinetic energy into heat via viscous dissipation, corresponding to an elevated turbulence dissipation rate [35]. In addition, the flow-blocking effect of the grids diverts the upper high-speed flow to impinge on the low-velocity lower water body, generating intense vertical momentum exchange and homogenizing turbulence in the vertical direction.

The combined arrangement of toe piers and suspended grids does not merely superimpose their individual effects; instead, it forms a sequential energy dissipation system consisting of flow-splitting deflection, flow-around shear, and burst of small-scale vortices. Toe piers first divide the single mainstream into narrow jets, which then flow around the

grids and increase the effective times of flow circulation around the grid members. The re-circulating wake flow induced by the grids conversely sustains the turbulence intensity behind the toe piers, creating a positive feedback loop.

4.3. Analysis of the Energy Dissipation Effect of Different Energy Dissipators Based on the Comprehensive Evaluation Objective Function

The stilling basin should not only meet the energy dissipation rate but also ensure its safe and stable operation to prevent the relevant hydraulic structures from being damaged by the water flow that has not been fully dissipated. Taking the relative near-bottom velocity and energy dissipation rate in the stilling basin as quantitative indicators, a comprehensive evaluation objective function is established, and finally, a better energy dissipation scheme is obtained.

Energy dissipation rate E

$$E = \frac{E_1 - E_2}{E_1} \times 100\% \quad (11)$$

$$E_1 = Z_1 + h_1 + \frac{\alpha_1 \bar{v}_1^2}{2g} \quad (12)$$

$$E_2 = Z_2 + h_2 + \frac{\alpha_2 \bar{v}_2^2}{2g} \quad (13)$$

where E_1 is the energy at the inlet section of the outlet sump, m; E_2 is the energy at the section 10 m downstream of the end of the stilling basin, m; Z_1 is the energy head at the inlet section of the outlet sump, m; Z_2 is the energy head at the section 10 m downstream of the end of the stilling basin, m; h_1 is the water depth at the inlet section of the outlet sump, m; h_2 is the water depth at the section 10 m downstream of the end of the stilling basin, m; α_1 and α_2 are kinetic energy correction coefficients; $\bar{v}_1$ is the velocity at the pre-jump section, taking the average velocity at the inlet section of the outlet sump, m/s; $\bar{v}_2$ is the average velocity at the section 10 m downstream of the end of the stilling basin, m/s; g is the acceleration due to gravity, $g = 9.8 \text{ m/s}^2$.

Set the maximum velocity at a height of 0.5 m from the floor slab along the length of the stilling basin as the maximum bottom velocity $v_{\max}$, and use the ratio of the maximum near-bottom velocity $v_{\max}$ of the floor slab to the average velocity $\bar{v}_1$ at the pre-jump section to represent the relative near-bottom velocity v :

$$v = \frac{v_{\max}}{\bar{v}_1} \quad (14)$$

Comprehensive evaluation objective function Y

$$Y = C_1 \times \frac{\Delta E}{E_1} + C_2 \times \frac{v_{\max}}{\bar{v}_1} \quad (15)$$

where $C_1 = -0.5$, $C_2 = 0.5$, referring to the analytic hierarchy process theory in the Saaty scaling system, where the scale value equals 1 and the normalized weight is 0.5 when two indicators are of equal importance, and drawing on the practice of adopting an equal preference coefficient $\alpha = 0.5$ for equally important evaluation dimensions in multi-criteria decision making described in References [36–38], this weight coefficient is adopted for the comprehensive evaluation objective function in this study. The lower the value of the comprehensive evaluation objective function Y , the better the energy dissipation effect of the stilling basin, which is a scheme with better comprehensive energy dissipation performance.

As can be seen from the energy dissipation rate calculation results in Table 4, the energy dissipation rate of the F1 traditional stilling basin is 69.1%, the energy dissipation

rate of the F2 stilling basin with toe piers is 70.97%, the energy dissipation rate of the F3 stilling basin with suspended grids is 71.56%, and the energy dissipation rate of the F4 stilling basin with combined arrangement of toe piers and suspended grids is 72.73%. At the design flow rate, compared with F1, the energy dissipation rate of F4 is increased by 3.63%, compared with F2 which is increased by 1.76%, and compared with F3 which is increased by 1.17%. The energy dissipation process of the stilling basin with combined arrangement of toe piers and suspended grids is more complex than that of the traditional stilling basin. Due to the placement of the toe pier energy dissipator, the discharged water flow is dispersed into multiple small water flows, changing the original water flow structure at the first section of the stilling basin. Also, due to the flow resistance and flow-splitting effects of the suspended grids, water flow accumulation and movement around the grids occur, changing the original hydraulic jump structure in the stilling basin, causing the hydraulic jump to occur earlier, and the water flow after the jump makes a movement around the grids, consuming some kinetic energy.

Table 4. Energy dissipation rate calculation results.

Scheme	Energy Dissipator	E_1 (m)	E_2 (m)	Energy Dissipation Rate E (%)
F1	None	1.272	0.393	69.10
F2	Toe pier	1.272	0.369	70.97
F3	Suspended grid	1.272	0.361	71.56
F4	Toe pier +suspended grid	1.272	0.347	72.73

As shown in Figure 11, after the toe pier auxiliary energy dissipator is installed in F1, the energy dissipation rate increases rapidly. The energy dissipation rates of F2 and F3 are not much different. After the toe pier–suspended grid combined energy dissipator is installed in F4, the energy dissipation rate increases significantly, showing a marked increase compared to F1.

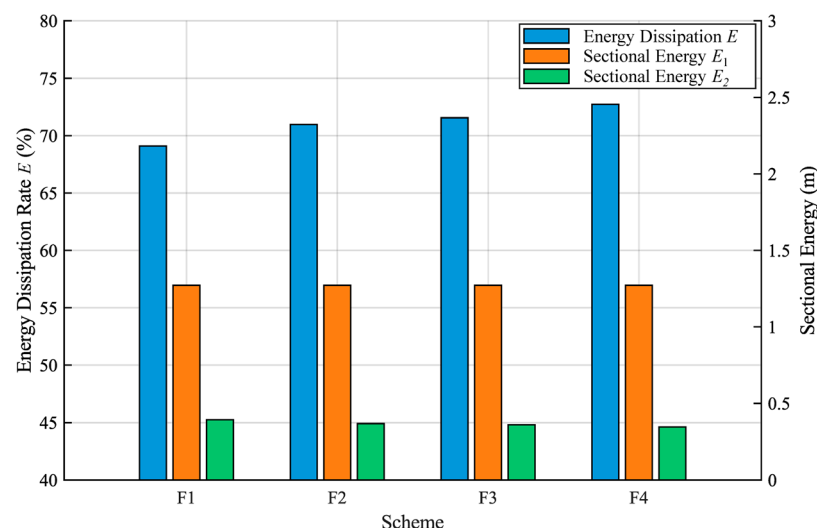


Figure 11. Energy dissipation rates under different energy dissipation schemes.

The calculation results of the relative near-bottom flow velocity v are listed in Table 5. For the average flow velocity at the pre-jump cross section, the calculation differences among various schemes are not obvious. The relative near-bottom flow velocity mainly depends on the maximum near-bottom flow velocity $v_{\max}$. As calculated above, the maximum near-bottom flow velocity of F1 is 8.0 m/s. The maximum critical flow velocity of F2 is 7.2 m/s. After the installation of the single suspended grids energy dissipation device, the maximum critical flow velocity in the sump reaches 7.4 m/s. After the installation of

the combined energy dissipator of toe pier and suspended grid in F4, the maximum near-bottom flow velocity in the stilling basin reaches 6.1 m/s. The scheme with the minimum relative near-bottom flow velocity is the energy dissipation scheme with the combined installation of toe pier and suspended grid, with a value of 1.65 m/s.

Table 5. Calculation results of the relative near-bottom flow velocity v .

Scheme	Energy Dissipator	$v_{\max}$ (m/s)	$\bar{v}_1$ (m/s)	v (m/s)
F1	None	8.0	3.69	2.17
F2	Toe pier	7.2	3.69	1.95
F3	Suspended grid	7.4	3.70	1.97
F4	Toe pier +suspended grid	6.1	3.70	1.65

The average flow velocity $\bar{v}_1$, maximum near-bottom flow velocity $v_{\max}$, and relative near-bottom flow velocity v at the pre-jump cross section of each scheme are shown in Figure 12.

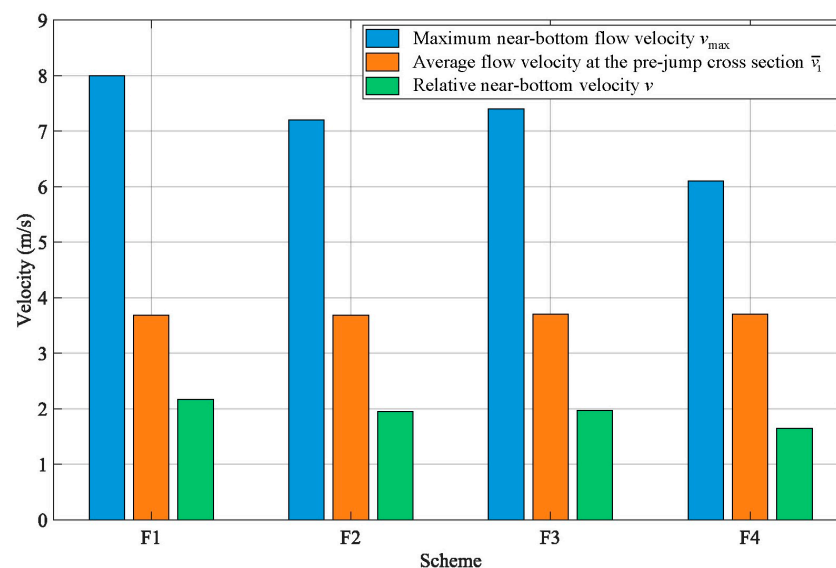


Figure 12. Various velocity in stilling basin under different schemes.

For the average flow velocity $\bar{v}_1$, at the pre-jump cross section, there is no obvious change trend among the schemes. For the maximum near-bottom flow velocity, the maximum near-bottom flow velocity of F2 is 10% lower than that of F1; the maximum near-bottom flow velocity of F3 is 8.75% lower than that of F1, but it increases compared with F2; the maximum near-bottom flow velocity $v_{\max}$ in the stilling basin of F4 decreases sharply, being 23.75% lower than that of F1.

As shown in Table 6 and Figure 13, the value of the comprehensive evaluation objective function Y of F1 is relatively high at 0.74, the hydraulic jump area is large, and the flow pattern in the basin is poor. The value of the comprehensive evaluation objective function Y of F2 is 0.62, which is 16.22% lower than that of the traditional stilling basin. The value of the comprehensive evaluation objective function Y of F3 is 0.63, which is 14.86% lower than that of the traditional stilling basin. The value of the comprehensive evaluation objective function of F4 is the lowest at 0.46, which is 37.84% lower than that of the traditional stilling basin, with the largest decrease. The vorticity distribution in the basin is concentrated and the flow pattern distribution is uniform, which can effectively avoid the scouring and damage of the stilling basin floor and improve the service life of the stilling basin. It can be found that after adding the combined energy dissipator of toe pier and suspended grid in the stilling basin, the energy dissipation rate is the highest, the relative near-bottom flow

velocity is the smallest, and the value of the comprehensive evaluation objective function Y is the smallest, indicating that its comprehensive performance is the best and it can effectively superimpose the advantages of each auxiliary energy dissipator.

Table 6. Calculation results of comprehensive evaluation objective function.

Scheme	Energy Dissipator	Energy Dissipation Rate (%)	v (m/s)	Y
F1	None	69.10	3.69	2.17
F2	Toe pier	70.97	3.69	1.95
F3	Suspended grid	71.56	3.70	1.97
F4	Toe pier +suspended grid	72.73	3.70	1.65

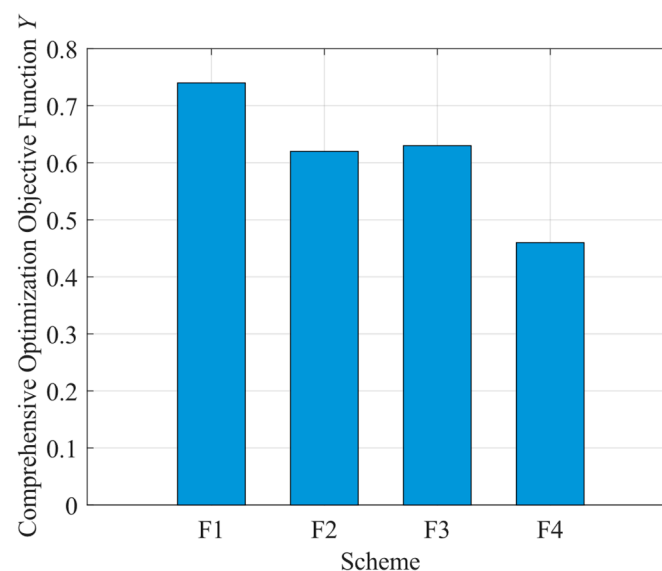


Figure 13. Comprehensive evaluation objective function Y under different energy dissipation schemes.

5. Conclusions

(1) The combined energy dissipator consisting of toe piers and suspended grids inside the pump outlet sump greatly improves the hydraulic characteristics and flow pattern distribution in the stilling basin. Compared with the conventional stilling basin, Scheme F4 reduces the maximum near-bottom flow velocity by 31% and achieves a maximum energy dissipation rate of $12.7 \text{ m}^2/\text{s}^3$, representing a 119% increase relative to the conventional Scheme F1;

(2) Scheme F4 achieves superior energy dissipation performance owing to the formation of a relay energy dissipation mode. The toe piers first split the single high-speed main flow discharged from the retaining weir into multiple discrete narrow jets, extending the contact perimeter of flow shear layers and forming a larger interface for turbulent energy production. The suspended grids generate flow disturbance around the jets and break large-scale recirculating vortices in the stilling basin into small-scale eddies with higher viscous dissipation efficiency. This stepwise energy dissipation via flow splitting, shearing, and mixing accelerates the conversion of turbulent kinetic energy into thermal energy, effectively mitigating the scouring risk imposed by concentrated high-speed flow on the basin floor from the perspective of flow structures.

(3) The comprehensive evaluation objective function established based on the relative near-bottom velocity and energy dissipation rate reveals that the evaluation index of Scheme F4 is 37.84% lower than that of Scheme F1, delivering optimal overall performance. Meanwhile, this scheme features a shorter hydraulic jump length. It addresses the energy

dissipation and anti-scour issues downstream of retaining weirs in low-head and large-flow pumping stations without extra land occupation, providing theoretical support and engineering references for the anti-scour and energy dissipation design of outlet structures and analogous hydraulic structures in similar pumping stations.

This study has certain limitations. Numerical analyses in this paper are only conducted under the typical condition of designed discharge and design operating water level. The adaptability of the combined toe pier-suspended grid energy dissipator under various hydraulic conditions has not been systematically investigated, and the generalizability of the present conclusions under off-design conditions requires further verification. Future research will establish multiple combinations of discharge and downstream tailwater levels to comprehensively evaluate the energy dissipation performance.

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Abbreviations

The following abbreviations are used in this manuscript:

LOWL	Lowest Operating Water Level
HOWL	Highest Operating Water Level
DOWL	Design Operating Water Level
VOF	Volume of Fluid
GCI	Grid Convergence Index
FVM	Finite Volume Method

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