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Analysis on water flow energy dissipation effect of curved spillway under different efficiency modes

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ABSTRACT

Spillways designed in hydraulic hubs can release floods and prevent floods from overflowing, which plays an important role in ensuring the safety of dams. To avoid the adverse effects caused by the water flow impact of the curved spillway, it is necessary to dissipate the energy of the water flow of the curved spillway. In this study, a reservoir is taken as the research object. Two plans for the water flow energy dissipation of the curved spillway are provided by the model test of the design of the curved spillway, namely the bottom flow composite energy dissipation and the multi-level drop energy dissipation. By studying the characteristics of water flow and the principle of energy dissipation under different working conditions, the respective energy dissipation effects of the two proposed schemes are obtained. The research results show that both energy dissipation schemes have good energy dissipation effect. Among them, the average efficiency rate of the outlet of the bottom flow composite energy dissipation spillway exceeds 80%; the multi-level drop energy dissipation design scheme is reasonably and well arranged, achieving the purpose of eliminating the energy of the spillway flow in stages and stages. To choose the best energy dissipation scheme and assure the curved spillway's design safety, multiple schemes may be used to compare the water flow energy dissipation impact of the curved spillway.

Keywords: Efficiency; Curved spillway; Energy dissipation; Water flow

1. Introduction

Spillways, as common discharge structures in hydraulic hubs, play an important role in releasing floods and preventing floods from overflowing. The most important purpose of setting up a spillway in a hydropower project is to ensure the safety of the dam, and the principle of adapting measures to local conditions should be followed when setting it up [1–4]. Spillway design should ensure symmetry, equal width and straight line to enhance the convenience of construction [5]. However, in the actual construction process, affected by various factors such as topographic conditions, project costs and the overall layout of the water conservancy project, the spillway often has diffusion and contraction sections, or it will be designed to be curved by twisting a certain angle on the plane [6–8]. The curved spillway generally adopts a circular arc curve with a radius greater than 10 times the groove width. Since the water flow in the curved section is subjected to the centripetal force, the surface water flow will turn into a lateral flow. This will cause the spillway's cross-section to lose its uniform distribution of water depth, causing the water depth on the outside of the spillway to be higher than the water depth inside, superelevating the water's surface. In short, this situation will complicate the water flow regime [9–12]. In addition, due to the complexity of the flow pattern of the cross-section, once the water flow becomes rapids, its direction will change due to the deflection of the spillway side wall. The downstream will also generate part of the wave

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disturbance, and the resulting shock wave will also affect the safety of the spillway. The shock wave may cause alternating crests and troughs on both sides of the spillway, which will worsen the issue of the water surface being elevated and, in certain situations, pose a danger to the safety of water conservation projects [13–15]. To ensure the construction safety of the spillway, it is necessary to dissipate the energy of the water flow of the curved spillway. Therefore, this experiment carried out reasonable calculation and design of water conservancy on the curved spillway in the hydraulic design, so as to improve the water flow state in the curved section of the spillway and suppress or eliminate the adverse effects of the water flow shock wave caused by the bending.

1.1. Related work

As a common discharge structure in hydraulic hubs, spillways play an important role in venting floods and preventing floods from overflowing, and have always been a research hotspot for researchers in various fields. Akbar M and other researchers have discussed the stepped spillway [16–19]. The study mainly analyzes the reasonable spillway model design without causing cavitation damage to the steps under the condition of ensuring safety and flood protection. Therefore, the experiment mainly analyzes the influence of step tread curvature on energy dissipation and pressure, and designs a spillway model with 14 steps. The final experimental results show that the proposed model can dissipate more energy than the simple spillway model [6]. Foroudi et al. [7] developed a 1:50 three-dimensional physical model to evaluate the impact of downstream channel width changes on the energy dissipation efficiency of arched planar stepped spillways. The experiment fully considered factors such as the width of the downstream channel and the peak width of the spillway. Experimental results show that the width changes when the spillway is flooded. At this time, it is necessary to adjust the model parameters reasonably to more accurately predict the maximum flood discharge that may pass. This study provides a better guidance for the improvement of the spillway. Li et al. [8] discussed the air-water flow characteristics of stepped spillways. The study found that the roughness density of the steps and the shape of the cavity can affect the energy dissipation performance of the spillway. The experiment studies the hydraulic performance of these parameters by means of numerical simulation and analysis of its air-water flow characteristics. The final experimental results show that the chamfered step edges can slightly enhance the energy dissipation of the spillway. The study showed good practical significance. Arjenaki and Sanayei [9] have studied the spillway geometry affecting the energy loss of stepped spillways. Five different staircases with different geometric shapes were selected for the experiment, and their energy dissipation effects were studied. The experiment uses Flow3D software and turbulence model for simulation. The final experimental results show that the D-shaped spillway with barriers has the best energy dissipation performance, which can increase energy dissipation by 15%.

Parsaie et al. [10] proposed a new type of spillway with a circular wave crest, and carried out a numerical analysis of the spillway's flow pattern, wave crest, velocity distribution on pressure, turbulence intensity, flood discharge coefficient, and energy consumption ratio analyze. The experiment uses relevant equipment to numerically observe the pressure distribution of the domed stepped spillway. Experimental results show that the proposed new spillway model can increase the maximum intensity of turbulent flow by 50%, and at the same time dissipate 90%–30% of the flow energy, which has a good application prospect. To determine the aeration efficiency of stepped spillways, Jahad et al. [11] conducted experiments on spillways with different step shapes and chute slopes. The experiment evaluated the effect of geometric changes by measuring dissolved oxygen concentration, free surface onset, and the water surface profile above the wave crest. And related experiments were carried out on a stepped spillway by utilizing a six-step configuration. The final experimental results showed that the steps of the quarter-round-end sill model improved performance by 10% in terms of aeration efficiency. Manogaran et al. [12] found that the water flowing through the spillway has high kinetic energy, which can cause serious damage and erosion to the spillway, weir bed and downstream of the river. In order to solve the above problems, the researchers carried out physical modeling. Experiments were performed to determine the minimum downstream velocity by using baffles. Experimental results show that this method can effectively reduce the water velocity. Experiments also suggest that chutes in dam spillways should avoid constriction, expansion or curvature to limit cross-wave generation and other unfavorable flow behavior. Yang et al. [13] conducted experiments and numerical experiments on different combinations of permeable branch dikes installed in the spillway bend, aiming to explore the specific impact of these combinations on flow characteristics and energy consumption rate. The experimental results show that the installation of permeable dikes at the bends of the spillway can improve the uniformity of the water surface to a certain extent. And after installing three permeable dikes, the uniformity of the water surface can reach 90.13%, and the energy consumption rate of the spillway can reach as high as 21.08%. Thus, the improvement effect of the permeable dike on the energy consumption rate of the spillway was verified.

To sum up, in the field of spillway research, many scholars have tried and explored it, and while they have gained certain research results, they also have many unavoidable limitations. Therefore, in order to ensure the construction safety of the spillway, this experiment attempts to carry out reasonable calculation and design of water conservancy on the curved spillway, so as to improve the water flow state in the curved section of the spillway, and then eliminate the adverse effects of the shock wave caused by the bending.

2. Model test of curved spillway

2.1. Hydraulic model design

This study selects a large reservoir as the research object, and its main buildings include spillways, earth dams, hydropower stations, water delivery tunnels, and water diversion buildings. The water level of the reservoir is 115.96 m, and the flood discharge is Q = 1,652 m^3/s. The designed energy dissipation flood frequency is P = 2%, the flood discharge flow is Q = 1,519 m^3/s, and the water level is 110.83 m. In addition, the design of the energy dissipation hydraulic model requires the selection of appropriate scales and materials. The designed scale is $\lambda_l = l_p/l_m = 50$ a normal model. Based on this model, the scales of the hydraulic parameters in the spillway are calculated. The calculation results are shown in the Table 1.

Table 1 is the hydraulic parameter scale calculation relationship table. As may be observed from the table, the hydraulic parameters of the curved spillway include length, pressure, velocity, flow, time and roughness. Among them, the scales of the last five parameters are obtained according to the length conversion, and the scale of the flow parameter is the largest, which is 177,677.67. After the scale parameters have been calculated, the proper hydraulic model material for spillway energy dissipation must be chosen. To reflect the flow state of the spillway under various working conditions without deviation, it is necessary to select appropriate model materials, mainly to meet the requirements of roughness. Therefore, when selecting simulation materials, choose materials with similar scales as much as possible to ensure the simulation accuracy precision. Under similar conditions of gravity, there is:

$$\lambda_n = \frac{n_p}{n_m} = \lambda_L^{1/6} \tag{1}$$

where n_p represents the roughness, among which the roughness of the downstream channel and the drainage structure are respectively $n_p = 0.033$, $n_p = 0.014$. According to the Formula (1), nm can be obtained respectively as 0.017 and 0.007. The model material used for the release structure may be plexiglass, and according to the results of the calculations above, its roughness ranges from 0.006 to 0.008. For the downstream channel of the reservoir, the treatment methods adopted are concrete plastering and fine gravel thickening. After completing the selection of model materials according to the scale parameters, the model is then installed. The device for installing the model needs to meet the accuracy requirements so that all errors are within the allowable range. Among them, the simulation errors of the building model and terrain elevation should be controlled between –0.03 and 0.03 mm and between –2 and 2 mm, respectively; and the errors of the plane distance, benchmark point and stylus zero point should be maintained at between –10 and +10 m, between –0.3 and +0.3 mm. Furthermore, the allowable azimuth deviation is between –0.1° and +0.1°.

The model test of the curved spillway needs to select certain equipment, mainly the water circulation system, including various facilities and equipment such as reservoirs, return tanks, power pumps, water distribution pipes, and flat water towers. Measurements of the pulsating pressure, water level, water flow, and water velocity are required for this model test, and various measurement items need the use of several equipment. Among them, the DJ800 multi-function monitoring system and pressure sensor developed by the Beijing Institute of Water Sciences are used for water pulsation and real-time pressure measurement; the water level tracker and water level probe are used for water level measurement; the rectangular water flow measurement is used for the model test [20]. What needs to be paid attention to when measuring the water weir is to take into account the requirements of range and precision control; the measurement of water flow velocity uses the portable flow meter developed by Nanjing Institute of Water Sciences, or the differential pressure measuring instrument developed and designed by Beijing Institute of Water Sciences. The flow rate of the rectangular weir can be calculated.

Table 1
Scale conversion of hydraulic parameters

Hydraulic parameters	Conversion relationship	Scale size
Length l	λ_l	50
Pressure p	$\lambda_p = \lambda_l$	50
Flow rate v	$\lambda_v = \lambda_l^{1/2}$	7.071
Flow Q	$\lambda_Q = \lambda_l^{5/2}$	17,677.67
Time t	$\lambda_t = \lambda_l^{1/2}$	7.071
Roughness n	$\lambda_n = \lambda_l^{1/6}$	1.919

$$Q = mB\sqrt{2g}H^{1.5} \tag{2}$$

Eq. (2) is the calculation formula for the discharge of a rectangular water measuring weir, in which, m represents the discharge coefficient and H represents the water head on the weir, and the discharge coefficient can be calculated according to the following equation.

$$m = \left(0.405 + \frac{0.0027}{H} - 0.03\frac{B_0 - B}{B_0}\right) \cdot \left[1 + 0.55\left(\frac{H}{H+P}\right)^2 \left(\frac{B}{B_0}\right)^2\right] \tag{3}$$

where B_0 represents the width of the diversion channel, and P represents the difference between the height of the upstream weir bottom and the height of the weir crest.

2.2. Hydraulic characteristics of curved spillway

The research on the hydraulic characteristics of the curved spillway is conducive to the study and comparison of different energy dissipation effects. The flow relationship of the curved spillway is different under different reservoir water level conditions. The relationship between the measured spillway reservoir water level and its flow under different construction conditions was studied, and the results shown in the table below were obtained.

Table 2 shows the relationship between the reservoir water level and the double-hole discharge. It is evident from the table that with the increase of the reservoir water level, the measured comprehensive discharge coefficient and the discharge rate of the double holes both increase. Among them, every time the water level of the reservoir rises by 1m, the discharge rate of the double holes increases by tens to hundreds of meters. Therefore, the double-hole leakage flow is released faster. In addition, from the perspective of water level, when the water level rises to 110 m and above, the increase of double-hole discharge is more than 1,000 m. As for the measured comprehensive discharge coefficient, when the water level is 107.3, 108.3 and 109.3 m, the comprehensive discharge coefficient is 0.409. Then with the increase of water level, the measured comprehensive discharge coefficient tends to decrease.

Fig. 1 is the relationship curve between the reservoir water level and the double-hole discharge in the test model. As shown by the figure that there is a positive correlation between the double hole discharge and the reservoir water level. The double hole discharge increases with the rise of the reservoir water level, which is consistent with the results shown in Table 1.

In this research scheme, when the gate of the curved spillway is fully open, a total of 15 water surface profile measurement sections are set, including 11 line measurement sections in the stilling basin and chute, and 4 line measurement sections in the gate chamber. Each measuring section of the line is set as 2 m from the left bank of the spillway is left, the centerline of the spillway is middle, and 2 m from the right bank of the spillway is right. The corresponding water surface elevation and measured water depth are respectively shown in the table below when the gate is fully opened, and the test is designed under two conditions of normal high water level and flood level.

Table 3 shows the water depth and water surface elevation along the spillway at the normal high water level of the reservoir. It is visible from the table that each line measurement section corresponds to a water depth and water surface elevation. The water depth of the 1–11 line measurement section on the left side of the line measurement section shows a decreasing trend, while the water depth of the 11–15 line measurement side section starts to increase, and the water surface elevation of the 1–13 line measurement section shows an increasing trend, before starting to decrease; for the middle and right side of the line measurement section, there is also a similar trend to the left side.

Table 2
Relationship between reservoir water level and double-hole discharge

Reservoir water level (m)	Double hole discharge flow (m)	Measured comprehensive flow coefficient (m^3/s)
102.3	33.388	0.314
103.3	102.509	0.341
104.3	197.105	0.357
105.3	318.152	0.374
106.3	465.160	0.392
107.3	638.454	0.409
108.3	805.627	0.409
109.3	993.395	0.409
110.3	1,170.244	0.408
111.3	1,368.117	0.407

3. Underflow composite energy dissipation

3.1. Underflow energy dissipation

The size, number, and positions of the T-shaped piers, the diversion piers, the position and depth of the plunge pool, as

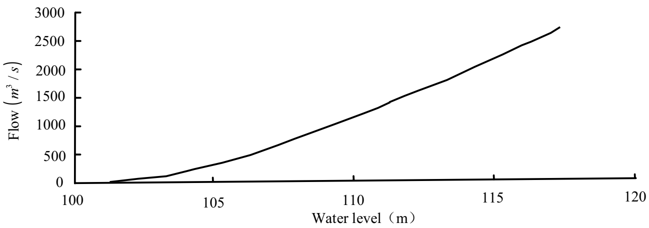

Fig. 1. Relationship between reservoir water level and double-hole discharge.

Table 3
Surface elevation and water depth of normal high water level spillway

Line measurement section	Left		Middle		Right	
	Water surface elevation (m)	Water depth (m)	Water surface elevation (m)	Water depth (m)	Water surface elevation (m)	Water depth (m)
1	106.49	6.69	107.61	7.81	108.25	8.45
2	106.94	5.64	106.54	5.24	106.41	5.11
3	103.81	5.01	103.41	4.61	103.58	4.78
4	102.65	3.85	102.22	3.42	102.51	3.71
5	101.87	3.59	101.87	3.59	101.87	3.59
6	101.15	3.21	101.15	3.21	101.15	3.21
7	101.62	4.45	100.29	3.12	100.29	3.12
8	99.26	3.16	99.26	3.16	99.26	3.16
9	90.40	2.01	90.41	2.01	90.41	2.01
10	83.14	0.77	84.16	1.78	86.26	3.89
11	76.61	0.25	78.98	2.61	80.87	4.51
12	76.41	0.95	77.98	2.52	79.48	4.02
13	70.37	1.71	70.18	1.51	70.36	1.70
14	71.03	2.37	70.18	1.51	70.55	1.88
15	73.39	2.22	78.03	6.87	75.89	4.72

well as the number and type of effective sills, have all been tested and studied in order to achieve the best energy dissipation effect during the energy dissipation of the flow in the curved spillway. Finally, the bottom flow composite energy dissipation method is selected to dissipate the energy of the spillway flow. The solution involves many different types of performance components, and these components are firstly described separately. The first is the inclined sill, which is used for diversion when energy is dissipated. Its main functions include energy dissipation and flow diversion. The inclined sill forms a hydraulic jump when energy is dissipated. When the water flow across the sill passes through the air, it is first aerated and then rolled over. In this way, part of the energy is eliminated. After setting the inclined bank, the positive axis of the spillway is perpendicular to the hydraulic contraction section at normal high water level, so that the flow velocity and depth of the spillway tend to be uniform in this way. The second is the water cushion pond. In this plan, two water cushion ponds are set, and their positions are obtained according to the measured water flow distance. The parameters of the two water cushion ponds are shown in the table below.

Table 4 shows the parameters of the two paddy ponds involved in the underflow composite energy dissipation scheme. It can be seen from the table that the position of the first water cushion pond is at the pile number 255.20–300.60 m, and its floor elevation is 79.391 m. The location of the second pad is at the pile number 391.15–434.05 m, and its floor elevation is 64.364 m. The purpose of setting up two water cushion ponds is to make the jumping water flow in the above-mentioned sloping sill fully roll over and increase the buffering effect on the water flow, so as to eliminate the excess energy of the spillway water flow.

Then there is the T-shaped pier. The purpose of setting up the T-shaped pier during the energy dissipation process is to increase the aeration of the water flow in the water cushion pond, so that more water flow energy can be consumed in the water cushion pond. Its energy dissipation effect is mainly reflected in the following aspects: First, the T-shaped pier can block the water flow, thereby forming a forced hydraulic jump, which can strengthen and stabilize the water quality. Secondly, the front of the T-shaped pier can shear the water flow, so that the water strands can shear each other to achieve the purpose of energy dissipation. Finally, the friction between the water body and the boundary of the T-shaped pier dissipates energy.

In the underflow composite energy dissipation scheme, the calculation formula of energy dissipation rate is as follows.

$$\eta_{02} = \frac{H_0 - H_2}{H_0}, \eta_{12} = \frac{H_1 - H_2}{H_1}, H_i = z_i + h_i + \frac{v_i^2}{2g} \quad i = 0,1,2 \quad (4)$$

Among them, H_0, H_1, H_2 represent the hydraulic head of section 1, section 8 and section 25, respectively, and the unit is m.

3.2. Hydraulic characteristics of underflow composite energy dissipation

In the underflow composite energy dissipation scheme, there are 20 water surface line measurement sections in the spillway. Among them, there are 16 line measurement sections in the stilling tank and the chute, and 4 line measurement sections in the lock chamber. Similarly, each line measurement section is set with three measurement points: left, middle and right. The flow velocity and water depth along the spillway under the bottom flow composite energy dissipation scheme are shown in the table below.

Table 4
Parameters related to the paddy pond

Parameter	Plunge pond 1	Plunge pond 2
Location	Chainage 255.20–300.60 m	Chainage 391.15–434.05 m
Base plate elevation	79.391 m	64.364 m

Table 5 shows the flow velocity and water depth along the spillway under the underflow composite energy dissipation scheme. It is visible from the table that the left, middle and right sides of each line measurement section correspond to a flow velocity and water depth along the spillway. Among them, two ramps are set at the measuring section of the 11th and 19th lines, respectively. The water depth and flow velocity on the three sides of the short side of the 11th line measurement side are large, both around 13 m. However, the water depth of the section measured by the 19th line is small, and the flow velocity on the left side is small. The two water carrying positions are located at the 12th and 20th line measuring sections, respectively. The height, distance and distance between the 12th line measuring sections are larger than those of the 20th line measuring sections, which are 9.01, 5.46 and 41.78 m, respectively.

Table 6 shows the efficiency rate under different working conditions in the underflow energy dissipation scheme. Among them, η_{01}' and η_{02} represent the energy dissipation rate of the spillway outlet from Section 1 and Section 8, respectively. From the table, it is clear that the energy dissipation rate of the spillway under the three working conditions of normal, design and verification are all above 80%, which shows that the energy dissipation effect under this scheme is better.

4. Composite energy dissipation of multi-stage falling water and underflow

4.1. Design of multi-stage water drop energy dissipation

The composite energy dissipation scheme of multi-stage falling water and bottom flow can also be applied to the water flow energy dissipation of curved spillways. The program has carried out some reconstruction of the reservoir. The rebuilt reservoir consists of five parts: inlet channel, chute, control section, performance section and tail trend, with a total length of 1,239.309 m. Drop water energy dissipation is to set 5 levels of drop barriers between each pile number of the spillway, so this scheme is called multi-level drop water energy dissipation, and the pile numbers and drop differences of each level of drop barriers are shown in the table below.

Table 5
Velocity and water depth along the spillway

Line measurement section	Left		Middle		Right	
	Velocity (m/s)	Water depth (m)	Velocity (m/s)	Water depth (m)	Velocity (m/s)	Water depth (m)
1	5.47	7.82	4.91	7.62	4.56	8.21
2	7.32	5.54	7.67	5.61	7.94	5.54
3	9.26	4.78	9.75	4.65	9.63	4.88
4	10.07	4.15	10.55	3.89	10.85	3.84
5	11.00	2.98	10.47	3.75	11.12	3.04
6	11.58	2.98	11.32	3.17	11.32	3.75
7	11.82	2.99	11.13	3.20	11.82	2.59
8	12.48	2.4	12.01	3.08	12.29	2.65
9	15.84	2.59	16.31	2.00	16.22	2.55
10	16.32	2.47	16.35	2.04	15.71	2.98
11 (hom 1)	15.97	2.18	14.01	2.99	13.51	2.69
12 (carrying water)	Height: 9.01		Pick distance: 5.46		High distance hurdle: 41.78	
13	12.56	3.2	/	/	13.64	3.03
14	9.98	5.09	/	/	10.66	4.32
15	7.31	5.17	9.74	6.89	10.88	5.86
16	7.71	3.81	10.68	4.62	11.24	4.65
17	11.57	2.60	12.33	3.17	12.74	3.34
18	5.36	4.89	10.82	5.27	11.39	5.68
19 (hom 2)	7.66	4.72	11.04	3.49	11.33	3.65
20 (carrying water)	Height: 5.62		Pick distance: 2.51		Overhead distance: 17.53	

Table 6
Energy dissipation rate under different working conditions

Condition	H_0	H_1	H_2	η_{01}	η'_{02}
Normal	45.24	42.51	8.49	81.20%	80.00%
Design	38.25	37.38	6.09	84.10%	83.70%
Check	37.77	35.3	5.02	86.70%	85.80%

Table 7 shows the five-level water drop of the spillway under the energy dissipation scheme of the piled water drop. It is visible from the table that the pile numbers of the first, second, third, fourth and fifth falls are 183, 183.6, 218.6, 249.9 and 323.6 m, respectively . It can be seen that the distance distribution between each level of drop is not uniform: the distance between the first level drop and the second level drop is about 75 m; the distance between the second level drop and the third level drop is about 35 m; The distance between the water and the fourth-level drop is about 30 m; the distance between the fourth-level drop and the fifth-level drop is about 80 m. This indicates that the distance between the three-level drops in the middle is closer than the two-level drops at the ends.

Design and arrange the multi-level drop energy dissipation components to better achieve the effect of hydraulic energy dissipation on the spillway. Set high and low sills on the steep trough section of the curved spillway, and set them obliquely. Improve the elevation of the stilling sill at the entrance of the curve and the submersion degree of the hydraulic jump inside the pool to reduce or eliminate the impact of the shock wave in the curve [21,22]. The specific design plan is as follows, respectively design the first level and the second level stilling sill. The calculation method of the size of the first level stilling sill is as follows.

Table 7
The pile number and drop difference of the five-stage drop of the spillway

Drop water	Chainage (m)	Drop (m)
Level 5 drop	323.6	2.65
Grade 4 drop	249.9	7.47
Level 3 drop	218.6	2.58
Secondary drop	183.6	5.85
Level one drop	108	0.92

$$Q=\left(a_1+h_1\right)\times b\times v \tag{5}$$

$$Q=m\sqrt{2g}\left(\int_0^b h_1+a_1-a_2+\frac{a_2-a_1}{b}y\right)^{\frac{3}{2}}d_y \tag{6}$$

$$a_1+h_2\approx\frac{h_c}{2}\sqrt{1+8F_{r1}^2}-1 \tag{7}$$

where v represents the flow velocity of the upstream water; to ensure that the water surface entering the pool is basically equal in the horizontal direction, $a_2>a_1$, this is to avoid the lateral water surface slope of the bend, so that the water depth entering the pool is uniform.

The second-level stilling pool is a diffused steep slope stilling pool, which is connected with the steep slope section. When the drop is small and the water flow is large, the water depth at the end of the steep slope decreases with the increase of the drop, so that the length and depth of the secondary stilling basin are positively correlated with the drop. At the same time, the water depth at the end of the steep trough will be close to the normal water depth, and it will flow at a constant speed, as long as the drop of the steep slope is high and the flow rate is small. When the water flow is in a state of uniform flow, even if the drop continues to increase, the water depth at the end will not be affected and reduced at this time. At this time, the length of the stilling pool is an appropriate length.

$$\frac{b_1h_1^2}{2}+\frac{Q^2}{gb_1h_1}+F_x=\frac{b_2h_2^2}{2}+\frac{Q^2}{gb_2h_2} \tag{8}$$

The above formula expresses the governing equation of the hydraulic jump in the diverging section of the horizontal bottom rectangular section. Among them, F_x represents the force of side wall and sill on water flow in direction x. There are generally two solutions to this equation, and the two solutions are relatively approximate, which are expressed as follows:

$$F_x=\frac{(b_2-b_1)(h_1^2+h_2^2)}{4} \tag{9}$$

$$F_x=\frac{(b_2-b_1)(h_1^2+h_1h_2+h_2^2)}{6} \tag{10}$$

For steep slope force reduction, compound section or trapezoidal section is used to reduce the amount of work. At this time, the side wall of the stilling pool will expand upwards, so that the water flow of the conjugate section has a water surface difference in both the water depth direction and the width direction. Therefore, it is necessary to optimize the design of the stilling basin. According to the existing engineering experience, the length of the secondary stilling basin is increased by 20 m. And a stilling sill is added at the entrance of the secondary stilling pool, thereby forming a steep slope diffusion-shaped stilling pool with a stilling sill at the entrance.

4.2. Comparison and evaluation of energy dissipation effect

Comparing the water depth and flow velocity of the stilling pool of the multi-stage falling water and bottom flow composite energy dissipation scheme, the effectiveness of the scheme is judged, and the specific results are shown in the table below.

Table 8 shows the water depth and flow velocity of the primary stilling pool. From the table, it is clear that when the flood frequency is 0.01%, the water depths on the left side and the middle side are the deepest in the middle, which are 8.25 and 10 m, respectively. On the right side, the water depth at the exit is the deepest, at 13.5 m. As far as the flow velocity is concerned, the flow velocity at the inlet is the highest, respectively 17.28, 14.98, and 14.64 m/s. The left side and the middle side have the smallest velocity in the middle, which are 2.94 and 6.33 m/s, respectively. On the right side, the flow velocity at the outlet is minimum. The optimized primary stilling pool can effectively eliminate the energy of the discharged water flow, and can effectively reduce the energy dissipation burden of the downstream secondary effect pool.

The multi-stage falling water and underflow composite energy dissipation scheme contains a variety of energy dissipation elements. Now select different typical sections, including the first-level and second-level stilling outlets, to evaluate their energy dissipation effects. It is more objective to evaluate from a quantitative point of view. The outlet energy dissipation rates of the first and second stilling basins in this scheme are calculated under different construction conditions and different starting points, and the calculation results are shown in the Table 9.

Table 8
Water depth and flow velocity of primary stilling pool

Flood frequency	Location	Water depth (m)			Velocity (m/s)		
		Entrance	Middle part	Exit	Entrance	Middle part	Exit
0.01%	Left	3.5	8.25	6.05	17.28	2.94	6.09
	Middle	4.75	10	7.5	14.98	6.33	7.73
	Right	4.2	11.8	13.5	14.64	10.49	9.92

Table 9
Energy dissipation rate at the outlet of the stilling basin under different working conditions

Condition	H_0	H'_0	H_1	H_2	η_{01}	η_{02}	η'_{01}	η'_{02}
Normal	36.78	34.55	13.31	5.6	63.80%	84.80%	61.50%	83.80%
Check	43.29	40.91	18.39	8.54	57.50%	80.30%	55.00%	79.10%
Design	39.11	37.27	15.16	6.12	61.20%	84.40%	59.30%	83.60%

Table 9 shows the calculation results of the efficiency rate at the outlet of the stilling basin under different construction conditions under the multi-stage falling water and bottom flow composite energy dissipation scheme. Among them, Wherein, H_0, H_0', H_1 and H_2 in the table represent the average head of spillway sections 1, 11, 16 and 21, respectively, and the unit is m. η_{01}, η_{02}, respectively represent the energy dissipation rates of the outlets of the first and second stilling basins calculated from section 1. η_{01}' and η_{02}', respectively represent the outlet energy dissipation rates of the first and second stilling basins counted from section 11. The average water head of each segment under the calibration circumstances is the biggest, measuring 43.29, 40.91, 18.39, and 8.54 m, respectively, as can be seen from the table. Under normal conditions, the average water head of each section is the smallest, which are 36.78, 34.55, 13.31 and 5.6 m, respectively. The cross-sectional average water head under the check state is between the other two working conditions. In terms of energy dissipation rate, the energy dissipation rate under normal working conditions is the highest, followed by the energy dissipation rates under design working conditions and checking working conditions. Among them, the efficiency rate of the first-level stilling pool exceeds 55%, and the energy dissipation rate of the outlet of the second-level stilling pool exceeds 80%. It shows that the layout of the energy dissipation design scheme is reasonable and good, achieving the purpose of disinfecting the energy of the spillway flow in sections and levels.

5. Conclusion

The energy dissipation treatment of the curved spillway water flow can ensure the safety of the hydraulic hub design process. This study takes a reservoir as the research object, designs the test model of the curved spillway, and selects the appropriate test materials. Finally, according to the characteristics of water flow, two energy dissipation schemes for curved spillway, namely compound energy dissipation under flow and multi-level drop energy dissipation, are proposed. By studying the characteristics of water flow and the principle of energy dissipation under different working conditions in the experiment, the respective energy dissipation effects of the two schemes are obtained. The research results show that in the underflow composite energy dissipation scheme, the average efficiency rate of the spillway outlet exceeds 80%. In the multi-level drop water energy dissipation scheme, the efficiency rate of the first-level stilling basin exceeds 55%, and the energy dissipation rate of the outlet of the second-level stilling basin exceeds 80%. It demonstrates that the design of the energy dissipation system is sound and effective and fulfills the goal of cleaning the energy of the spillway flow in sections and levels. This study can illustrate the effectiveness of the two energy dissipation schemes, but it is only for a specific project, and its wide applicability needs further study.

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