EXPERIMENTAL STUDY ON THE ENERGY DISSIPATION MECHANISM OF THE TWO-STAGE STILLING BASIN IN LOW FROUDE NUMBER FLOW

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ABSTRACT

The two-stage stilling basin is an effective way of solving the problem of energy dissipation in low Froude (Fr) number flow. However, to date, there have been little research on the shape parameters and energy dissipation mechanisms of the two-stage stilling basin. To address this issue, the body parameters and their sensitivity in the two-stage stilling basin with low Fr flow are studied by combining theoretical analysis and a physical model. At the same time, based on the optimal body of the stilling pool determined by experiments, the hydraulic characteristics of single-stage and two-stage stilling basin with low Fr flow are studied and compared. The results show that the parameters of the stilling basin such as length, depth, and end sill height all have thresholds. If a parameter exceeds the threshold, the undular or repelled downstream hydraulic jump tends to occur in the first stage stilling basin, while the water surface fluctuation in the second stage stilling basin increases significantly. Under the condition of low Fr flow, the adaptation interval of the two-stage stilling basin to the downstream tail water level increases significantly , and the fluctuation of the downstream water level is smaller, which can effectively solve the problem of large fluctuation of the downstream water surface of the single stilling basin and improve the energy dissipation rate.

Keywords: low Froude number water flow; two-stage energy dissipation basin; body parameters; hydraulic characteristics; energy dissipation mechanism

1. INTRODUCTION

The energy dissipation problem of low Fr flow is always one of the challenges in the field of hydraulics for its low energy dissipation rate, large residual energy after the jump, severe turbulence of the water flow, serious scour of the riverbed and the bank slopes [1]. In addition, low Fr flow has poor adaptability to the downstream tailwater level. When the downstream water level drops more and the tailwater level increases, the outflow will form a repelled hydraulic jump, causing more severe damage. Engineering practices show that the two-stage or multi-stage stilling basin has good adaptability to conditions such as terrain, incoming flow and downstream water level. Besides it can obtain a stable hydraulic jump, improve energy dissipation rate, and meet the requirements of energy dissipation for erosion-control in low Fr flow, becoming an effective way to solve the problem of energy dissipation in low Fr flow [2-5]. Chen Zhongru et al. [6] initially summarized the energy dissipation characteristics and body parameters of the multi-stage stilling basin by analyzing the design and operation of multi-stage stilling basin of the existing projects, but Fr of the flow studied is between 3.47 and 7.41. Wu Zirong et al. [7] summarized and analyzed some hydraulic characteristics of multi-stage stilling basin with low Fr flow based on the hydraulic model test of Dongjin Gate, but did not study the body parameters of the stilling basin. Wang Sheng et al. [8] took Angu Hydropower Station as an example, and proposed an energy dissipation scheme for the two-stage stilling basin with continuous ridge type by hydraulic model test.

The above studies provide the basis for the applications of two-stage and multi-stage stilling basin and the studies of hydraulic characteristics, but they are mostly limited to specific projects, lacking of studies on body parameters and energy dissipation mechanisms of two-stage or multi-stage stilling basin. In this paper, taking the two-stage stilling basin as the research object, the shape optimization, hydraulic characteristics and energy dissipation structure characteristics of the two-stage stilling basin are studied under the condition of a low *Fr* flow, especially for the *Fr* <2.5 flow

2. EXPERIMENT OVERVIEW

2.1 Model Design

According to the purpose of the study, a flume model is designed. The model has a length of 14m; the open channel has a width of 0.4m and a height of 0.7m for the downstream channel. The position coordinate system is that the midpoint of the bottom of the leading edge of thec stilling basin is coordinate origin, the x-axis is horizontally downstream, and the y-axis is upward.

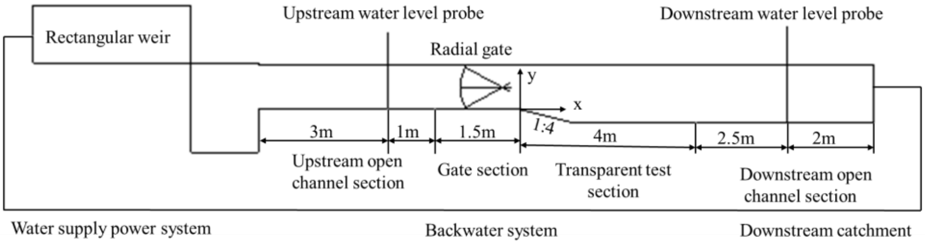


Figure 1. Schematic diagram of the longitudinal and position coordinates of the model layout

The measurement content involves flood discharge, water level, velocity, water surface line, wave height and so on. The discharge is measured by a measuring weir; the water level is read by the water level probe; the water surface line and wave height are measured by the wireless transmission wave height meter measurement system; the flow velocity is measured by a propeller-type current meter.

2.2 The Test Flow Conditions

According to the previous research results, if *Fr* <2.5, the surface of flow does not form a eddy region, but a undular hydraulic jump. Therefore, the *Fr* of flow in the test should be controlled in this interval. Taking the section x = -40cm where the water flow is more uniform and the water surface line is more stable as the calculated section, when the flood discharge of incoming flow is 27L/s, the calculated *Fr* of incoming flow is 1.36, as shown in Table 1. For this reason, the flood discharge Q = 27L/s that is the unit width discharge q = 0.068m^2/s is selected for test.

Table 1 Relationship between *Fr* and flow conditions

Flood discharge *Q*/ （L s^{-1}）	**The unit width discharge *q*/ （m^2 s^{-1}）**	**Gate opening /cm**	**The upstream water depth /cm**	**Water depth at x=-40cm section /cm**	***Fr***
27	0.068	9.0	10.92	6.3	1.36

2.3 Experiment Scheme

Under the unit width discharge q = 0.068m^2/s, the slope in front of the stilling basin is 1: 4 according to 'The Standard of Design Sluice' ; the length of the basin is initially determined by Eq. (1) to Eq. (3). Body shape and parameters are shown in Figure 2.

$$E_0 = h_c + \frac{q^2}{2g\varphi^2 h_c^2} \qquad (1)$$

Where: E_0 represents overall water head of the section in front of the stilling basin, which can be calculated by $E_0 = h + p + \frac{q^2}{2gh^2}$; h_c represents the water depth of vena contracta; φ represents the velocity coefficient, taken 0.95; and h_c can be calculated by iterative method.

$$h_{c2} = \frac{h_c}{2}\left(\sqrt{1+8Fr^2} - 1\right) \qquad (2)$$

The conjugate depth(h_{c2}) can be calculated.

$$L_j = 6.9(h_{c2} - h_c) \qquad (3)$$

The length of hydraulic jump(L_j) can be calculated, and the length stilling basin can be calculated according to the empirical formula L_k=（0.6～0.8）L_j .

The downstream water lever H_d takes the elevation z=0 as the reference origin, because the elevation of the downstream basin bottom will change with the test. And in the following tests, the water level values take z=0 as the reference.

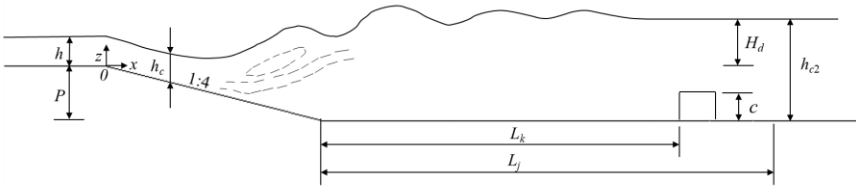


Figure 2. Body structural and parameters of single-stage stilling basin

After calculation, the initial body of the single-stage stilling basin is: p = 10cm, L_k = 70cm (the tail-weir is at the section of x = 110cm), and c = 6cm.

The problems existing in the single-stage stilling basin are studied through experiments, and two-stage stilling basin is proposed to solve the problems, as shown in Figure 3.The length of the stilling basin is calculated by Eq. (1) to Eq. (3), and sufficient surplus length is set aside at the same time. Take the length of the first-stage basin $L_k^1=66$ cm, and the length of the second-stage basin $L_k^2=80$ cm. Based on this, the body optimization test of the two-stage stilling basin is carried out.

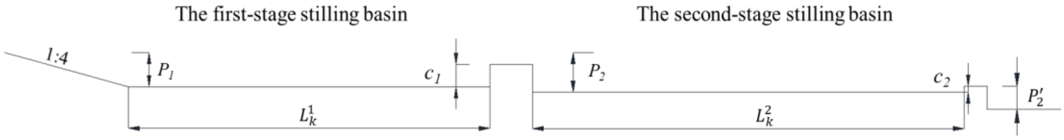


Figure 3. Body structural and parameters of two-stage stilling basin

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Depth of the stilling basin

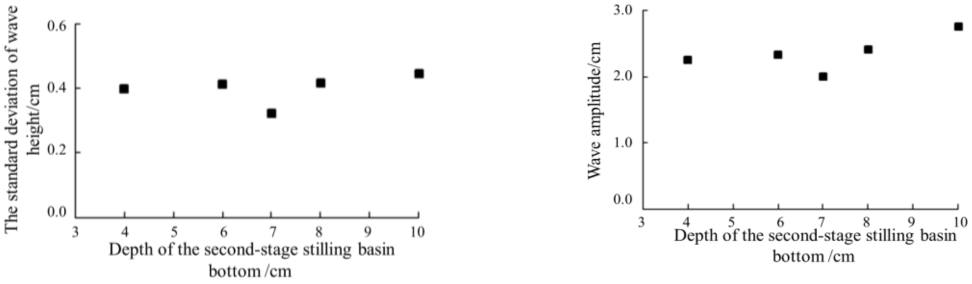
3.1.1 Depth of the first-stage stilling basin

Firstly, take p_1=8cm, the depth of the basin changes is relatively small compared with the single-stage stilling basin, and the optimization space for the two-stage stilling basin is small, so no experimental analysis is conducted. Under the condition of p_1= 4cm, two groups of tests are carried out. Taking the first-stage end sill height c_1=4cm, an undular hydraulic jump is formed in the first-stage stilling basin under the condition of the downstream water lever H_d=6.5cm, and as the downstream water level drops, there is still a undular hydraulic jump in the basin, which means c_1 is too large. Taking c_1= 3cm, a steady hydraulic jump is formed in the first-stage stilling basin under the condition of a higher downstream water level, however if the downstream water lever is less than H_d=6.7cm, a repelled downstream hydraulic jump occurs, which means c_1 is too small.

Under the appropriate tail water level, there is a suitable value between 3cm and 4cm, with which a steady hydraulic jump could occur. But at this time, the flow pattern in the stilling basin is very sensitive to the height of the end sill and the downstream tail water level, and it is difficult to form a steady hydraulic jump, so p_1=4cm is not desirable. The reasonable depth of the first-stage stilling basin bottom should be in 4cm to 8cm. Therefore, p_1=6cm is initially determined.

3.1.2 Depth of the second-stage stilling basin

According to the analysis of tests, the relationship between the standard deviation of wave height (a) and wave amplitude (b) at the downstream section of x= 240cm and the depth (p_2) of the second-stage stilling basin are shown in Figure 4. The standard deviation of the wave height is the arithmetic square root of the variance, which represents how far the data sets deviate from the average and its value can reflect the stability of the data sets and the magnitude of its change.



(a) the standard deviations of wave height (b) wave amplitude

Figure. 4 Relationship between water level fluctuation at x=240cm section and depth of the second stage stilling basin

According to fluctuation characteristics of the downstream water level, if the depth of the second-stage stilling basin p_2 =7cm, the fluctuation of the downstream water level is significantly smaller than others. It indicates that the depth of second-stage stilling basin bottom needs to be ensured at an appropriate value (or interval), otherwise the downstream water level will fluctuate greatly. Therefore, p_2=7cm is initially determined.

3.2 Height of the end sill

3.2.1 Height of the end sill of the first-stage stilling basin

Under the condition of the downstream water level H_d=4.22cm, when c1=5cm and c1=4cm, the flow pattern in the pool and the water level (Z/cm) along the pool were observed, respectively. The water surface lines are shown in Figure 5 and Figure 6.

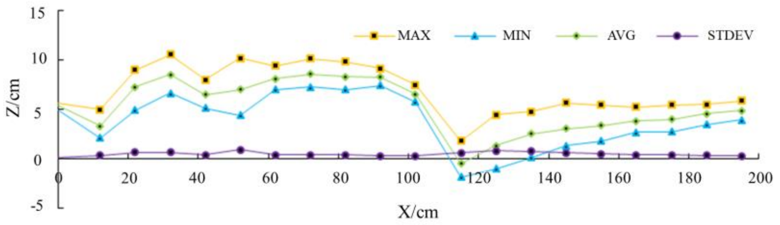


Figure 5. Average surface line along the pool at H_d =4.22cm, c_1=5cm.

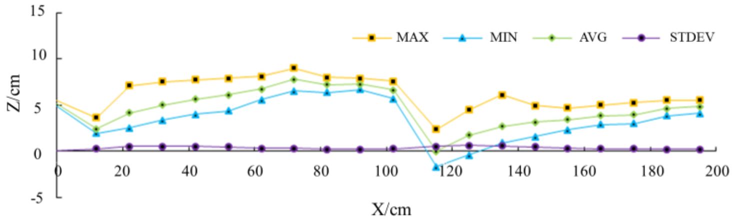
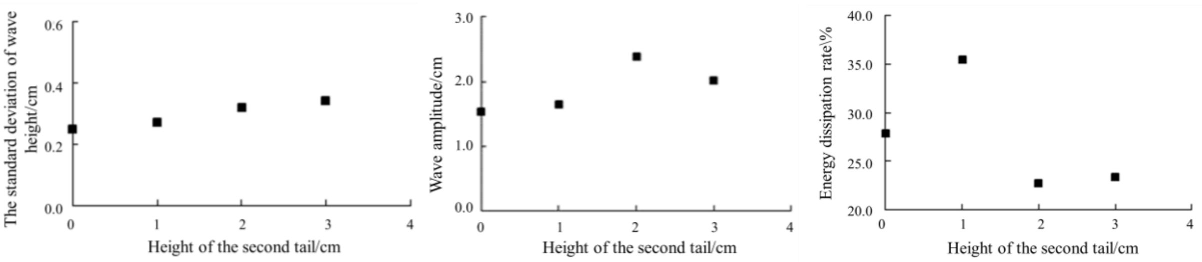


Figure 6. Average surface line along the pool at H_d =4.22cm, c_1=4cm.

From the flow pattern of the first-stage stilling basin, it can be known that if p_1=6cm and c_1=3cm, the repelled downstream hydraulic jump occurs in the stilling basin, which indicated that c_1=3cm is too small. If c_1= 5cm, the undular hydraulic jump occurs in the stilling basin, so c_1=5cm is too large; if c_1=4cm, the steady hydraulic jump occurs in the stilling basin, and the fluctuation of the downstream water level is smaller, so it is appropriate to take c_1=4cm.

3.2.2 Height of the end sill of the second-stage stilling basin

Tests are carried out to optimize the height of end sill of the second-stage stilling basin（c_2） ,the flow pattern of which is similar, embodied in that the steady hydraulic jump can be formed in the first-stage and second-stage stilling basin, and the downstream water level has a slight drop. Taking the fluctuation of water surface at x=240cm section as the basis for optimal selection, the relationships between the fluctuation characteristics of water surface at x = 240cm section and the energy dissipation rate and the height of the end sill under four groups are shown in Figure 7.



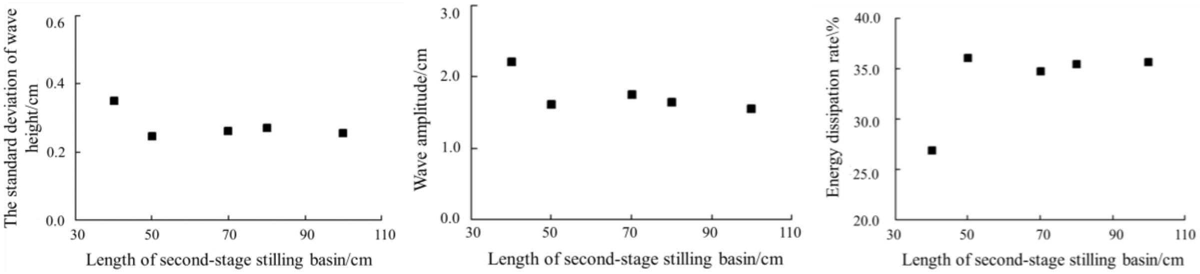
(a) The standard deviations of wave height (b) Wave amplitude (c) The energy dissipation rate

Figure. 7 Relationship between water level fluctuation and energy dissipation rate at x=240cm section and the height of the second tail

From the characteristics of wave attenuation, the lower the height of the second-stage end sill, the smaller the standard deviation of wave height, and the better the effect of wave attenuation. From the perspective of the overall energy dissipation rate of the stilling basin, if c_2=1cm, energy dissipation rate is significantly higher than the other three cases. So, c_2=1cm is initially determined.

3.3 Length of the stilling basin

In the above tests, the length of the stilling basin is initially determined based on theory and experience. After other body parameters are determined by experiments, some tests are carried out to verify the treatment. Under the conditions of five lengths of the two-stage stilling basin: L_k^2 =40cm, L_k^2 =50cm, L_k^2 =70cm, L_k^2 =80cm, L_k^2 =100cm, the measurement results of the water surface fluctuation are shown in Figure 11 (a) and (b), and the energy dissipation rate is shown in (c).



(a)The standard deviations of wave height (b) Wave amplitude (c) The energy dissipation rate

Figure 8. Relationship between water fluctuation and energy dissipation rate at x=240cm section and the length of the second basin

As shown in Figure 8, if L_k^2 >40cm, the standard deviations of wave height at the section x=240cm are very close, which are 0.25cm, 0.26cm, 0.27cm and 0.25cm respectively; if L_k^2 =40cm, the standard deviation of the wave height is 0.35cm, which is significantly larger than other values, indicating that if the length of stilling basin is smaller, it has a greater impact on the flow pattern of the water surface. If the length of stilling basin exceeds a certain value, the length of stilling basin has little effect on the flow pattern of the water surface. From the perspective of the overall energy dissipation rate of the two-stage stilling basin, if L_k^2 =40cm, the energy dissipation rate of which is significantly lower than others; if L_k^2 >40cm, the overall energy dissipation rate fluctuates around 35%, and the amplitude of the change is not more than 2%. From the perspective of wave attenuation and energy dissipation, the test results show that there is a suitable limit value for the length of the two-stage stilling basin.

Based on the above-mentioned series of the body optimization tests of two-stage stilling basin, the optimal two-stage stilling basin body and parameters are determined, as shown in Figure 9.

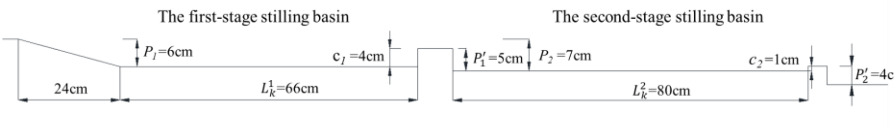


Figure 9. Schematic diagram of the body structural and parameters in two-stage stilling basin

4. COMPARISON AND ANALYSIS OF TEST RESULTS OF HYDRAULIC CHARACTERISTICS

4.1 The adaptive interval of the tail water level

4.1.1 The adaptive interval of the tail water level of single-stage stilling basin

According to the tests, the thresholds of tail water level of the stilling basin are listed in Table 2, in winch H_{d1}, H_{d2} and H_{d3} respectively represent the lower limit value of tail-water level for the occurrence of undular hydraulic jump in the single-stage stilling basin, the upper and lower limit value of tail-water level for the occurrence of large fluctuation of the downstream water, and H_{d1}, H_{d2} and H_{d3} are called the threshold of tail water level of the stilling basin. If $H_{d2}<H_d<H_{d1}$, the steady hydraulic jump can occur in the basin, the effect of energy dissipation is great, and the downstream flow is relatively smooth, which is the downstream tail water level range that the stilling basin can adapt to. If $H_{d3}<H_d<H_{d2}$, the downstream water fluctuates greatly, and if $H_d<H_{d3}$, the downstream water level will fall, forming a secondary hydraulic jump.

Table 2. The threshold of large fluctuation of the water surface in and out of single-stage stilling basin

Fr	$\boldsymbol{H_{d1}}$（cm）	$\boldsymbol{H_{d2}}$（cm）	$\boldsymbol{H_{d3}}$（cm）	$\boldsymbol{H_{d1}-H_{d2}}$（cm）
0.99	8.38	8.34	6.45	0.04
1.36	8.66	8.37	6.66	0.29
1.87	9.02	8.44	5.97	0.58
2.26	9.70	8.36	6.21	1.34

（$H_{d1}-H_{d2}$） is the adaptive interval of the stilling basin to the downstream tail water level. From Table 2, it can be seen that the adaptive interval of tail water level is very small under low *Fr*. With the increase of *Fr*, the adaptive interval has increased, which indicates that the flow with low *Fr* is more prone to occur undular hydraulic jump.

4.1.2 The adaptive interval of the tail water level of two-stage stilling basin

As the same as the single-stage stilling basin, the threshold of the tail water level of the two-stage stilling basin is analyzed. Under different *Fr* conditions, the values of H_{d1}、H_{d2} and H_{d3} are listed in Table 3.

Table 3. The threshold of large fluctuation of the water surface in and out of two-stage stilling basin

Fr	$\boldsymbol{H_{d1}}$（cm）	$\boldsymbol{H_{d2}}$（cm）	$\boldsymbol{H_{d3}}$（cm）	$\boldsymbol{H_{d1}-H_{d2}}$（cm）	$\boldsymbol{H_{d2}-H_{d3}}$（cm）
0.99	8.01	5.59	4.51	2.42	1.08
1.36	8.21	5.56	4.42	2.65	1.14
1.87	9.26	5.53	4.51	3.73	1.02
2.26	9.80	5.60	4.62	4.20	0.98

It can be seen from Table 3 that the basic law of the adaptability of the two-stage stilling basin to the tail water level is the same as that of the single-stage stilling basin. The adaptive interval ($H_{d1}-H_{d2}$) of the downstream tail water level increases with the increase of *Fr*. However, the values of ($H_{d2}-H_{d3}$) remain basically the same under different *Fr* conditions. In addition, with the increase of *Fr*, the amplitude of H_{d2} and H_{d3} is not large, while the amplitude of H_{d1} is obvious and it increases with the increase of *Fr*. This also shows that in the stilling basin, the larger the *Fr* is, the more easily the hydraulic jump occurs , and can adapt to larger tail water level interval.

4.1.3 Comparison of the adaptability to the tail water level

Based on the adaptability of the stilling basin to the tail water level and the *Fr*, the flow pattern is subdivided into four areas according to the downstream tail water level from low to high: drop area of the downstream water surface, the large fluctuation area of the downstream water surface, adaptive area and undular hydraulic jump area in the basin as shown in Figure 10 and Figure 11.

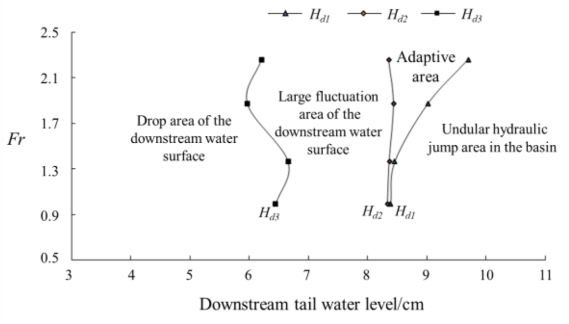


Figure.10. Schematic diagram of adaptive zoning of the tail water level of single-stage stilling basin

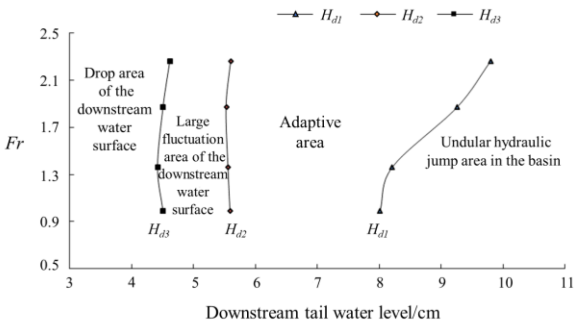


Figure 11. Schematic diagram of adaptive zoning of the tail water level of two-stage stilling basin

It can be seen that when the single-stage stilling basin is changed to the two-stage stilling basin, the drop-off area and the large fluctuation area of the downstream water surface are greatly reduced, and the large fluctuation area of the downstream water surface of the original single stilling basin is changed into the adaptive area. Thus, the adaptive area increases significantly, and the stilling basin can adapt to the lower tail water level.

4.2 Characteristics of wave attenuation

The characteristics of wave attenuation of the stilling basin mainly refer to reducing the fluctuation of the downstream water level, which can be used as one of the control indexes to evaluate the advantages and disadvantages of the stilling basin. Under the condition of Fr=1.36, the standard deviation of wave height and wave amplitude of each stage stilling basin measured are listed in Table 4.

Table 4. The characteristics of wave attenuation of the flow at 0 + 240 section

H_d（cm）	**The standard deviation of wave height（cm）**			**Wave amplitude（cm）**		
	Single-stage stilling basin	**Two-stage stilling basin**	**Gradient**	**Single-stage stilling basin**	**Two-stage stilling basin**	**Gradient**
6.27	0.23	0.21	-9%	1.77	1.74	-2%
7.36	0.32	0.22	-31%	2.81	1.8	-36%
9.84	0.31	0.28	-10%	2.56	2.26	-12%

It can be seen that the standard deviation of wave height and Wave amplitude of the two-stage stilling basin at 0 + 240 section decreased compared with the single-stage stilling basin, and the decrease is the largest under the condition of middle tail water level H_d=7.36cm. According to the adaptive partitioning of the tail water level of each stage stilling basin (Figure 10 and Figure 11), when H_d=7.36cm, it is in the large fluctuation interval of the downstream water surface for the single-stage stilling, but it is in the adaptive interval for the two-stage stilling.

4.3 Energy dissipation rate

Taking section 0-2cm as the energy calculation section before dissipating energy, and section 0 + 240cm as the energy calculation section after dissipating energy. The comparison of the energy dissipation rate of the two-stage stilling basin proposed and single-stage stilling basin is shown in Table 5.

Table 5. The comparison of the energy dissipation rate of the two-stage and single-stage stilling basin

Tail water level（cm）	**Energy dissipation rate（%）**		**Difference（%）**	**Gradient（%）**
	Single-stage stilling basin	**Two-stage stilling basin**		
6.27	27.8	37.5	9.7	34.9
7.36	18.7	24.0	5.3	28
8.44	13.9	17.5	3.6	25.9
9.47	9.2	10.7	1.5	16.3
9.84	6.5	6.9	0.4	6.2

According to Table 5, when Fr=1.36, the energy dissipation rate of the two-stage stilling basin is higher than that of the single-stage stilling basin at each tail water level, and the lower the tail water level is, the more the energy dissipation is. Under the condition of the tail water level of 6.27cm, the energy dissipation rate of the two-stage stilling basin is 34.9% higher than that of the single-stage stilling basin.

5. CONCLUSIONS

（1）Under the condition of low Fr flow, the parameters of the two-stage stilling basin such as length, depth and end sill height all have thresholds. If the depth of the stilling basin bottom is not in this interval, the undular or repelled downstream hydraulic jump tends to occur in the first-stage stilling basin. The lower the height of the end sill is, the better the effect of wave attenuation is. If the length of the stilling basin is less than the threshold, the flow pattern in the stilling basin deteriorates, and the energy dissipation ratio decreases.

（2）Under the condition of low Fr flow, the two-stage stilling basin could change the large fluctuation interval of the water surface of the original single-stage stilling basin into the adaptive interval, which could improve the adaptive interval of the stilling basin to the downstream tail water level. With the decrease of Fr, the adaptive interval of the two-stage stilling basin to the tail water level increases, which could effectively solve the problem of large fluctuation of the water surface of the single-stage stilling basin.

（3）Under the condition of Fr=1.36, the energy dissipation rate of the optimized two-stage stilling basin is significantly improved compared with the single-stage stilling basin, and with the decrease of the tail water level, the increase is more obvious. The maximum increase value of energy dissipation rate given by the test is 34.9%.

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