Research on Cavitation Characteristics and Control Measures of Horizontal Swirl Spillway Tunnel

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Abstract. The swirling chamber of the horizontal swirling energy dissipation is the key part to form the swirling flow, but the swirling chamber and the rising sill are also sensitive parts of cavitation. In order to improve its anti-cavitation performance, the side wall aeration and pressure should be increased. This paper proposes to set up an annular aeration sill in the middle and upper part of the shaft, and use a vent pipe to supplement the air under the sill to increase the aeration volume of the swirling chamber and the ascending sill. Both the monitoring data and the flow surface inspection show that the noise of the cavitation water flow in the swirling chamber of the horizontal swirling tunnel is weak. There are no obvious signs of negative pressure and cavitation. The ventilation facilities of the shaft section are effective, and the water flow is fully air-entrained. The water flow aeration can effectively protect the surface of the flow channel. This measure can effectively solve the anti-cavitation problem.

1. Introduction

To build power stations on large rivers in high mountains and valleys, due to the constraints of terrain and other conditions, it is often necessary to build several large-sized diversion tunnels. The diversion tunnel has only been used for a few years\cite{1}. It is a temporary building, but it has a huge investment. Therefore, how to transform the diversion tunnel into a permanent spillway tunnel after the completion of the diversion task has always been a concern of the world\cite{2}.

Judging from the current research progress at home and abroad, in the process of rebuilding the diversion tunnel into a permanent flood discharge building, the swirling internal energy dissipation tool has the characteristics of simple structure, flexible layout, and high energy dissipation rate. It can adapt to complex terrain and geological conditions, and it is relatively simple to use the reverse shaft to turn the machine\cite{3}. Therefore, the swirling internal energy dissipater is a new type of energy dissipation measure suitable for high water head and large flow in deep mountains and valleys. It is a feasible plan for high dam construction diversion tunnel to be converted into flood discharge tunnel\cite{4,5}.

2. Engineering condition

Since the 1960s, a large number of experiments and researches have been conducted on the cyclone energy dissipater at home and abroad, but there have been no reports of the completion and operation of the project\cite{6}. Combining the characteristics of a certain engineering geological conditions, construction
conditions and operating requirements, through program comparison and demonstration, experimental research, design calculations, and structural analysis and demonstration, the type of horizontal swirling energy dissipation flood discharge tunnel is determined. In the design process, through normal pressure, decompression single hydraulic model test and overall hydraulic model test, the building shape, discharge capacity, flow rate and flow pattern, energy dissipation rate, fluctuating pressure, aeration and corrosion reduction and improvement of cavitation resistance are studied. The body shape of each part of the building is continuously optimized, and the current body shape is determined after structural analysis and demonstration.

The horizontal swirling energy dissipation flood discharge tunnel consists of an open inlet weir gate section, a shaft section, a swirling chamber, a horizontal swirling tunnel section, a vent, a cushion pond section, and a drainage tunnel. The layout and figure of the horizontal swirling energy dissipation flood discharge tunnel is shown in Figure 1.

![Figure 1. The layout and figure of the horizontal swirling energy dissipation flood discharge tunnel](image)

In order to ensure the formation of a stable rotating water flow in the swirling hole and fully aerate the water flow, to achieve the purpose of aeration reducing corrosion and increasing the energy dissipation rate, a vent hole is provided at the upstream end of the horizontal hole. The vent hole extends upward into the top of the weir gate section to communicate with the atmosphere. The ventilation hole is arranged separately from the shaft. The diameter of the ventilation hole is 4.5m, the thickness of the concrete lining is 0.6m, and the diameter after lining is 3.3m. The surrounding rock of the shaft wall is equipped with anchor rods and consolidated grouting.

3. Ventilation characteristics

3.1. Ventilation volume of the whirling chamber ventilation well
During the opening of the gate, the air flow in the vent well of the swirl chamber is very turbulent. When the gate opening is small, some parts of the same section are aired in, and some parts are exhausted. When the gate opening is greater than 65%, the wind speed in the vent well of the swirl chamber are greater than zero. After the gate opening exceeds 70%, the wind speed at most measuring points increases rapidly. After the gate is fully opened, the wind speed value at each measuring point tends to stabilize.

3.2. Ventilation volume of the annular aeration vent
In the test, a total of 15 Pitot tubes were arranged in the 5 vent holes of the annular aeration sill, and 3 Pitot tubes were installed in each vent hole.
3.2.1. Wind speed variation characteristics during gate opening

When the gate opening is less than 11%, the wind speed at each measuring point is close to 0. When the gate opening reaches 11%, the wind speed at each measuring point increases rapidly. When the gate opening increases to about 32%, the increase in wind speed decreases. The gate opening exceeds 80%~85%, the wind speed at each measuring point tends to the steady state value. The test found that when the gate opening is in the range of 32% to 80%, the air-carrying capacity of the annular aeration sill is the strongest, and the wind speed of the vent hole is also greater than the wind speed value after the gate is fully opened.

3.2.2. Ventilation characteristics of the vent hole after the gate is fully opened

After the working gate is fully opened, the wind speed at each measuring point changes greatly. The difference between the instantaneous maximum wind speed and the instantaneous minimum wind speed is generally between 20m/s and 50m/s. Experimental tests show that during the operation of the spillway tunnel, the cavity downstream of the annular aeration sill is in fluctuating changes, and the amount of air carried by the water flow changes periodically.

After the working gate is fully opened, the arithmetic mean values of the vent hole wind speeds of the three water passing tests are 112.8m/s, 106.1m/s and 121.3m/s, respectively. The 5 vent holes of the corresponding annular aeration sill have been tested for. The average air volume of a single hole in the area: 35.2m³/s, 33.1m³/s and 37.8m³/s. It can be seen from the test results that the average air-carrying capacity of the annular aeration sill is basically unchanged.

In terms of the magnitude of the wind speed obtained from the monitoring, it has exceeded 50% to 100% specified in the specification, and the ventilation volume of the vent hole is also much larger than the model measurement result, indicating that the shaft aeration facility has a strong air-carrying capacity.

3.2.3. Negative pressure in the downstream cavity of the annular aeration sill

During the gate opening process, when the gate opening is greater than 13%, the downstream cavity of the annular aeration sill is closed and the pressure in the cavity gradually decreases. The measured minimum instantaneous pressure is close to -80kPa, and the minimum hourly average pressure is about -60kPa.

The negative pressure of the cavity is one of the indicators of the adequate ventilation of the aeration facility. The negative pressure of the cavity should ensure the smooth air intake of the cavity, and the negative pressure of the cavity should not exceed -5kPa. The negative pressure of the cavity under the sill is monitored this time, which is -25kPa~ -35kPa, which has exceeded the specified value, indicating that the flow area of the vent hole is slightly smaller and the ventilation wind speed is too large. From the previous monitoring results of ventilation, under the existing body shape conditions and prototype test conditions, the increase in cavity negative pressure is caused by the increase in the length of the cavity, which is inevitable related to the enhancement of the water flow's air-carrying capacity and the increase of ventilation.

Prototype monitoring found that during the opening of the working gate, a large amount of water vapor is first discharged from the whirl chamber ventilation well, and part of the water vapor is condensed near the inlet of the ventilation well. When the working gate is fully opened, the ventilation well will take in air. Due to the high intake wind speed, the condensed water around the ventilation well is gradually sucked into the ventilation well. Affected by the boundary conditions at the inlet of the ventilation well and the water flow in the swirling chamber, the flow field of the wind speed measurement section is not uniform during the opening of the working gate and after the gate is fully opened. The ventilation well of the whirling chamber is ventilated smoothly, and the ventilation volume is basically the same as the model test value. The ventilation effect of the annular aeration sill in the shaft section is good.
4. Pressure characteristics
The measuring points F-YX-03S~F-YX-06S are located in the cavity of the annular aeration sill. During the opening of the gate, when the opening of the working gate is less than 13%, there is a free falling flow in the shaft, and the orifice of the annular aeration sill not closed. The upper and downstream cavities of the ring sill are connected, and the pressure of each measuring point is close to the atmospheric pressure. When the gate opening is 13%~80%, the pressure of each measuring point drops rapidly, and the minimum instantaneous pressures of the four measuring points are respectively: -78.14kPa, -67.89kPa, -68.06kPa and -64.27kPa. When the gate opening is greater than 80%, the pressure at each measuring point fluctuates near the steady-state value. The pressure time process line of the typical measuring point F-YX-03S is shown in Figure 2.

![Pressure time process line of measuring point F-YX-03S during the opening process of the running test gate](image)

The measuring points F-YX-07S~F-YX-10S are at the end of the cavity downstream of the aeration sill. During the opening of the gate, when the opening is less than 3%, the pressure at each measuring point is equal to the atmospheric pressure. When the gate opening is 3%~20%, the diffused water flow touches the section, and the pressure at each measuring point is greater than the atmospheric pressure. The maximum time-averaged pressures of the four measuring points are: 26.8kPa, 10.8kPa, 16.86kPa and 10.0kPa. When the gate opening is 20%~75%, the pressure of each measuring point drops rapidly, and the measured maximum instantaneous pressure are -65.76kPa, -62.28kPa, -31.55kPa and -86.67kPa. When the working gate opening is greater than 75%, the pressure of each measuring point increases rapidly and tends to steady state value. After the working gate is fully opened, the pressure at the four measuring points fluctuates around atmospheric pressure, and the hourly average pressure is less than zero. The pressure time process line of the typical measuring point F-YX-07S is shown in Figure 3.

![Pressure time process line of measuring point F-YX-07S during the opening process of the operating test gate](image)
5. Other characteristics

1) In order to analyze whether cavitation will occur during the operation of the spillway tunnel, seven hydrophones are arranged in the spillway tunnel. Data analysis results show that the high frequency characteristics (above 50kHz) of the water flow noise signal are basically similar, but the background noise level is different.

The measuring point F-YX-01S is located downstream of the overflow surface. When the working gate is opened to 20.8%, the high-frequency noise rises rapidly. The change curve is pulse-shaped. When the gate opening increases to 73%, the noise level decreases rapidly. According to the change characteristics of the high-frequency noise curve and the characteristics of the flow downstream of the overflow surface, it is judged that the gate opening is in the range of 20.8% to 73%, and primary cavitation occurs downstream of the overflow surface. In the initial stage of gate opening, there is free flow in the shaft. After the water flows over the overflow surface, it escapes at the place where the curvature of the lower part of the weir surface changes greatly, forming a cavity. When the pressure in the cavity is lower than the gasification pressure, cavitation is generated. After the opening of the working gate is greater than 73%, there is a submerged flow in the shaft, and the pressure at the measuring point F-YX-01S is relatively high. The downstream of the overflow surface is under positive pressure, and there will be no water flow cavitation.

See Table 1 for the upgrade increase in high-frequency noise at each measurement point.

| Measuring point number | Noise when the gate is opened (dB) | Background noise (dB) | Maximum noise level (dB) | Maximum noise level increase (dB) |
|------------------------|----------------------------------|-----------------------|--------------------------|----------------------------------|
| F-YX-01S               | 43.8                             | 47.3                  | 61.8                     | 14.5                             |
| F-YX-04P               | 42.0                             | 45.5                  | 58.9                     | 13.4                             |
| F-YX-05P               | 44.6                             | 48.1                  | 56.1                     | 8.0                              |
| F-YX-08P               | 43.0                             | 46.5                  | 56.9                     | 10.4                             |
| F-YX-09P               | 43.0                             | 46.5                  | 59.6                     | 13.1                             |
| F-YX-10P               | 41.3                             | 44.8                  | 67.6                     | 22.8                             |
| F-YX-11P               | 41.2                             | 44.7                  | 55.9                     | 11.2                             |

Based on the above-mentioned high-frequency noise variation characteristics of the measurement points, it is preliminarily determined that the cavitation noise monitored by these measurement points originates from the same cavitation source, that is, the shear-type cavitation that occurs near the ridge of the spin-off chamber. The maximum increase in noise level monitored by each measuring point is 22.8dB, indicating that the cavitation intensity is not very strong. Shear-type cavitation occurs in the water flow, and the cavitation bubbles are also collapsed in the water flow. This type of cavitation will not adversely affect the building.

2) In the prototype operation monitoring test, the conductivity meter and the resistance aerator are used to measure the aeration concentration distribution of the water flow near the wall after the gate is opened, closed and fully opened. The aeration concentration distribution law measured by the three running tests is basically the same. The main frequency of the pulsation of aeration concentration reflected by each measuring point is 0.2 Hz or its multiples. On the whole, the aeration effect of the annular aeration sill of the cyclone tunnel is better, which plays a role of aeration and erosion reduction.

3) Cavitation monitoring shows that there are two types of water cavitation during the operation of the spillway tunnel. During the opening of the gate, cavitation noise occurred downstream of the overflow weir and near the lifting ridge of the swing chamber after it is fully opened, but the cavitation intensity is weak. It will not endanger the safe operation of flood discharge structures.

4) After the test, the inspection showed that the concrete on the overflow surface of the spillway tunnel had local spalling. These local spalling damages were all caused by the defects of the concrete surface on the overflow surface, and the local spalling damage area did not increase with the increase of
the flood discharge time. The trend indicates that the hydraulic characteristics of the spillway tunnel and the operation effect of aeration and erosion reduction facilities are better.

5) Prototype monitoring found that when the ventilation volume of the annular aeration ridge is small, the ventilation volume of the swirling chamber is large. When the ventilation volume of the annular aeration ridge is large, the ventilation volume of the swirling chamber is small. The aeration of the annular aeration ridge has a certain compensation effect on the ventilation of the swirling chamber of the flat cave.

6. Conclusion
The monitoring results show that the ventilation facilities using the shaft aeration sill and the whirling chamber ventilation play an important role in protecting the lower section of the shaft and the whirlpool from cavitation damage well. The ventilation volume of the whirling chamber is similar to the model test results. The aeration effect and ventilation wind speed of the annular aeration ridge of the vertical shaft section are far greater than the model test results. When similar engineering designs are carried out in the future, the vent pipe area of the vertical shaft section should be appropriately enlarged to control the wind speed and the negative pressure of the cavity.

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