Design and Operation Characteristics of the Horizontal Swirl Flood Discharge System

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Abstract. It is one of the effective methods to increase the reliability of flood discharge buildings with high water head and reduce the project cost to transform the diversion tunnel of temporary buildings into permanent spillway by using the horizontal swirl flood discharge system. Based on Gongboxia hydropower station and combined with prototype monitoring, this paper studies and analyzes the key points of shape layout, structural characteristics and operation effect of horizontal swirl flood discharge system, the results show that the horizontal swirl flood discharge system has strong adaptability to topographic and geological conditions, good energy dissipation effect and hydraulic characteristics, stable inlet and outlet flow pattern, stable cyclone cavity, no obvious signs of adverse negative pressure and cavitation erosion, no adverse structural vibration and dynamic response, and safe operation of the spillway tunnel.

1. Introduction
To build a power station in a high mountain valley, several diversion tunnels are usually required. However, it is not economical for the diversion tunnels with large investment to be used only during the dam construction period. Therefore, it is a common solution to transform the diversion tunnels of temporary buildings with one tunnel for multiple purposes[1-2], such as Sichuan Ertan Hydropower station took the diversion tunnel as part of the tailwater tunnel of the power station, Gansu Liujiaxia hydropower Station transformed the diversion tunnel into a spillway tunnel, and The Geland Channel in the United States transformed the diversion tunnel into a drainage hole. However, there is little practical experience in transforming diversion tunnel into spillway tunnel, and the successful application of swirling energy dissipation in Gongboxia hydropower station makes the hydraulic industry see its broad application prospect.

According to engineering practice experience and research progress, the working principle of swirl energy dissipation is to use the water rotation movement to consume most of the water energy in the flow passage and transfer only part of the energy to the downstream. It has the advantages of high energy dissipation rate, simple structure, flexible layout, easy ventilation and aeration, etc., especially suitable for power stations with high head and large flow[3]. According to the different locations of the rotating flow, the swirling energy dissipation can be divided into vertical shaft cyclone and horizontal cyclone. For example, Sichuan Shapai adopts vertical shaft cyclone dissipation, and Gongboxia hydropower Station adopts horizontal cyclone dissipation.
is a large drainage structure with a flow rate of more than 1000 m³/s, a head of more than 100m and a good operation effect for the first time in China. It is of landmark significance in the design, research and engineering application of swirling energy dissipation spillway tunnel in China [4-5].

Based on Gongboxia hydropower station and combined with prototype monitoring, this paper studies and analyzes the key points of shape layout, structural characteristics and operation effect of horizontal swirl flood discharge system, in order to enhance the understanding of the horizontal swirl flood discharge system, and the research results can provide a reference for related projects.

2. Layout key points of horizontal swirl flood discharge system
Horizontal swirl flood discharge system is adopted, and its layout characteristics shall meet the following requirements: The requirements for the operation mode and discharge capacity of the building, the problems of anti-air erosion and energy dissipation of buildings with high water head flood discharge are solved properly to ensure the safety of the buildings. The layout and structural design of the spillway tunnel are carried out in combination with the topographic and geological conditions to maximize the advantages and avoid the disadvantages as much as possible. Simple shape, easy to construct. As much as possible to use the established diversion tunnel, reduce the amount of reconstruction projects, save project investment, etc.

Horizontal swirl flow energy dissipation is the use of water flow in a horizontal drainage tunnel in the rotary motion, improve the side wall pressure, flow and side wall friction, process significant growth, to increase the flow of the frictional losses, reduce the energy purpose. Therefore, the longer the hydrocyclone for energy dissipation, vortex period is shorter and to get higher energy dissipation and must be combined with other energy dissipation measures, such as water cushion pond, and the side wall pressure increase and the side wall of the decrease of the flow velocity, to improve the structure of the cavitation characteristics.

Horizontal swirl tunnel and water cushion pond are the main parts of water flow energy dissipation, which should be considered comprehensively in terms of energy dissipation and cavitation resistance. A spin chamber is the key part of formation of hydrocyclone, but the spiral chamber and rose camp site is sensitive parts of the cavitation cavitation erosion, in order to improve the cavitation erosion resistance should improve the side wall of the aeration and stress, can adopt the following measures, such as an annular aerator is set in the upper part of the shaft, and a ventilation pipe is used to replenish air under the air bar. An open and slope cutting shape is adopted in the guide bar, and a contraction ring is set at the inlet of the cyclone section. Long gradient section is adopted at the inlet of the water cushion pond, and streamline strip is adopted at the outlet edge and bottom, which can not only improve the anti-cavitation performance and ensure the operation safety, but also meet the requirement of energy dissipation rate. If the outlet of the original diversion tunnel is provided with a cantilever nose, when the downstream water level is relatively high, the flow can be connected with the surface flow, when the downstream water level is low, the stream-picking connection can be realized. Therefore, there is no need to reconstruct the stream-nose ridge at the outlet of the diversion tunnel, and it will not increase the scouring and silting of the downstream channel.

The spillway tunnel on the right bank of Gongboxia has a designed water head of over 100 meters and a spillway flow rate of over 1032 m³/s. The length of the diversion tunnel is 1130m, including 724m of the tunnel section (including 271.7m of the plane bend). In addition, the geological conditions at the entrance and the shaft are complex, with highly weathered rock strata distributed. In order to make full use of the diversion tunnel as far as possible and adapt to the layout of the bend, it is advisable to adopt the way of energy dissipation in the tunnel combining the short swirl section with the water cushion pond, so as to reduce the flow velocity of the combined section, reduce the amount of reconstruction work and save the project investment.

Flood discharge tunnel of Gongboxia hydropower station level rotary flow energy dissipation through experimental study type selection, design of lining structure research, prototype water test research, finally determine the layout[5]: From top to bottom by the overflow weir, shaft, vent, swirl hole, the water cushion pond, retreat of tunnel, the axis of the water intake with diversion tunnel axis
Angle 45°. The inlet of the horizontal swirl flood discharge system adopts completely submerged flow pattern, the vertical shaft is equipped with aerator and vent to supplement air, the starting chamber and the water cushion pond are all in the curved section of the tunnel, the water cushion pond not only co-dissipates energy with the cyclone section, but also plays the role of adjusting the flow pattern, so that the flow pattern of the water withdrawal tunnel is stable and other technologies are adopted for the first time. The layout of the horizontal swirl flood discharge system is shown in Figure 1, and the engineering photo of the turning chamber is shown in Figure 2.

![Figure 1. The horizontal swirl flood discharge system arrangement.](image1)

(a) Transverse section diagram along the inlet axis  
(b) Longitudinal section diagram along the diversion tunnel axis

![Figure 2. Engineering photo of the turning chamber.](image2)

3. Key points of structural analysis of the horizontal swirl flood discharge system

The reconstruction section of Gongboxia spillway tunnel includes the horizontal swirl energy dissipation shaft and the reconstruction section of xiaping Tunnel, each place are located in the hub of rock under seepage prevention system of upstream III level terrace base, strong rock weathering, fault fracture, lithofacies change is big, poor geological conditions. After the reservoir impoundment, all parts of the reconstruction section will be immersed in the reservoir water, and the building will bear greater external water pressure. In order to ensure the structural safety, the consolidation grouting in reconstruction period of each part and system anchoring bolt reinforcement, and in the water cushion pond and annealing tunnel roof arch horizontal drain system, set up in order to reduce the web of pressure, and these factors will influence web of stress distribution, reasonable web of pressure value is very important to ensure the structure safety and economic rationality. In addition, the reconstructed section of the lower level tunnel of the horizontal cyclone spillway tunnel is formed by lining of the original diversion tunnel lining, and a joint surface is formed between the old and new concrete lining, which will affect the bearing capacity of the building. Therefore, the reconstruction of spillway tunnel should focus on the influence of new and old concrete combined with the building bearing capacity, the distribution of external water pressure, the influence of drainage hole, consolidation grouting of surrounding rock and system anchor on the improvement of structure bearing capacity, etc., and conduct in-depth research on the engineering characteristics.
According to the practice of Gongboxia experience, when considering effect of consolidation grouting, role in the concrete lining of the outside of the web of pressure head, such as cyclone hole section (Figure 3), considering consolidation grouting circle of surrounding rock of the outer lining of pressure head value than when small regardless of the surrounding rock consolidation grouting circle 10 m, peripheral consolidation grouting of rock mass shows lining have certain effect to reduce the pressure of web. For example, in the water cushion pond section (Figure 4), the seepage pressure outside the lining decreases by 5m~31m compared with that without considering the drainage effect, especially when the drainage hole is set in the top arch of the tunnel, which indicates that the layout of the drainage hole can effectively reduce the external water pressure of the lining. Therefore, consolidation grouting should also be considered as one of the factors for the reduction of external water pressure in the future design of similar engineering structures, and different reduction coefficients should be adopted for the top and bottom when considering the action of drainage holes. Under the action of external pressure, consolidation grouting and system bolt are beneficial to reduce the stress of lining under the action of external pressure, thus improving the bearing capacity of lining structure against external pressure. The existence of the interface between the new and the old concrete lining will make the old concrete bear a large proportion of external water load. During the construction, the surface of the old concrete lining is chiseled and inserted with bars, which can increase the integrity of the lining structure and improve the stability of the lining structure. It is necessary to set up the consolidation grouting, system bolt and rebar. In addition, horizontal hydrocyclone energy dissipation spillway tunnel is adopted in the shaft, and its energy dissipation rate can reach more than 80%. The flow velocity in the retreat water tunnel section can be generally less than 15m/s. In general projects, diversion tunnel can be used as the retreat water tunnel.

![Figure 3. Schematic diagram of water pressure distribution outside concrete lining in hydrocyclone tunnel section (m).](image)

![Figure 4. Schematic diagram of water pressure distribution outside concrete lining in water cushion pond section (m).](image)

4. **Operation effect of the horizontal swirl flood discharge system**

The horizontal swirl flood discharge system of Gongboxia hydropower station is the first time both at home and abroad to run the prototype monitoring of vortex flow energy dissipation, combined with the structure and hydraulics related monitoring results, show that the operation of the flood discharge
tunnel of Gongboxia hydropower station level rotary flow energy dissipation effect is good, the discharge of meet the requirements, shape structure design is reasonable, the dissipation (84%) and aeration erosion is remarkable.

4.1. Structure operation
During the operation of spillway tunnel, whether the shaft is full flow or free flow, the dynamic response of synchronous monitoring structure is very small and the vibration is extremely weak. The maximum vibration acceleration measured at each measuring point is only 0.046g. The vibration of the top of the gate, the traffic bridge and the dam is relatively small, and the measured maximum vibration acceleration is 0.01g, indicating that the flow pulsation has little influence on the top buildings, the traffic bridge and the dam during the operation of the spillway tunnel, and no obvious vibration sensation is observed. During the operation of the spillway tunnel, the high speed water pulsation did not cause obvious vibration of the drainage building.

The water flowing through the spillway tunnel has little influence on rock displacement, seepage pressure outside the concrete lining and measured value of steel reinforcement. The rock displacement before and after the water flowing through the spillway tunnel is 0.1mm-0.2mm. The variation of osmotic pressure gauge is generally about 0.01mpa. The measured value of steel reinforcement meter is generally about 1MPa. The maximum tensile stress of reinforcement is below 80MPa, which is far less than the strength of reinforcement. In addition, the bedrock of the spillway tunnel is closely combined with the old concrete lining and the new and old concrete lining, and the measured value of the seam gauge tends to be basically stable, within about 0.5mm.

4.2. Hydraulics operation
The monitoring shows that at the beginning of the working gate opening, the water flow falls along the overflow weir, the surface of the water tongue is white, and the free flow in the shaft is gradually transformed into submerged flow with the increase of the gate opening. When the working gate is fully opened, the water flow in the upstream reservoir area and the inlet is stable, the water flow on the shaft surface is vertical axis roll, and the maximum fluctuation range of the shaft water level is 1.9m. During the opening process of the inlet gate and the fully open operation of the spillway tunnel, the flow pattern in the tunnel changes steadily without adverse flow pattern or the phenomenon of water cap. The residual amplitude of the roof in the fully open operation of the gate is more than 65%, which meets the operating conditions of the flow pattern of the spillway tunnel. The use of 65.5m long water cushion pond can play a good role in adjusting the flow pattern of the water. The pressure at the flow surface of the spillway tunnel is normal. The pressure time process line of the measuring point at the turning chamber section during the gate opening is shown in Figure 5. When the gate opening is greater than 80%, the pressure fluctuates near the steady state value (value after the gate is fully opened). Placed in the back of the tunnel flow video monitor, first recorded in the gate opening and closing process and open running water cushion pond in downstream retreat the flow regime inside of the tunnel, further verify the energy dissipation design of this project, but also eliminates the people of this way of energy dissipation can cause back flow within the tunnel instability or adverse flow of worry.

The upstream wall of the turning chamber has smooth ventilation in the ventilation well, and the annular aerator in the shaft section has good ventilation effect. The downstream cavity of the aerator has two stable forms, the cavity is stable and the aeration effect is good. It is found that when the annular aeration gap is small, the air volume of the turning chamber is large. When the annular aeration gap is large, the air volume of the turning chamber is small. Annular aerator is necessary to set annular aerator on the upper part of the shaft, because it compensates the ventilation of the rotating chamber of the flat hole.
Figure 5. Pressure time process line of measuring point in the turning chamber section during the gate opening.

At the measuring point downstream of the overflow surface at the entrance of the shaft, when the working gate opening is 20%, the high-frequency noise rises rapidly. When the gate opening is 70%, the noise level decreases rapidly and then fluctuates around 47dB. The noise level of each measuring point of the turning chamber increases rapidly after the working gate is opened. When the gate is opened to 80%, the noise intensity tends to be stable. During the operation of the spillway tunnel, there are two types of water flow cavitation, and cavitation noise occurs in the downstream of the overflow weir during the gate opening process and near the lift of the lifting chamber after full opening, but the cavitation intensity is weak and the duration is short, so it will not endanger the safety of the spillway building.

5. Conclusion
The diversion tunnel of Gongboxia Hydropower Station has been transformed into the horizontal swirl spillway tunnel, which is the first large-scale reconstruction project with a flow of over 1000m³/s and a head of over 100m in China, the practice shows that the horizontal swirl flood discharge system on the topography and geological conditions of strong adaptability, good energy dissipation effect and hydraulic characteristics, it is to improve the large and medium-sized water conservancy and hydropower engineering hub layout flexibility, reliability, and increase the flood discharge of high water building a relatively good way to reduce the project cost, the actual project has significant economic benefits and popularizing value.

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