RESEARCH ON FLOOD DISCHARGE OPERATION AND REGULATION TECHNOLOGY OF LARGE HYDRAULIC PROJECT BASED ON INTAKE VORTEX OF OVERFLOW SURFACE ORIFICE

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ABSTRACT

There are vortex phenomena to different extents at the intake of some positions of overflow surface orifices in the operation and scheduling of gates of the existing projects. The long lasting occurrence of intake vortex with high frequency is a great challenge for safety operation and weak gate structure of a dam. To improve its operation safety, relying on a composite model of three research means (prototype observation of flood discharge of large projects, numerical computation and large scale integral hydraulic model), we explore the formation mechanism of intake vortex in surface orifice, the characteristics of vortex in front of gate and the assessment of impacts of vortex on operation of gates and hydraulic structures during flood discharging from multiple perspectives, and analyze the relationship between the formation of vortex and the gate opening as well as the water level in upstream and downstream. By means of the numerical model and the physical model, we forecast the flow field in front of a dam and the intake vortex characteristics in operation conditions of different series of flood discharge facilities, analyze the impact of different reservoir water levels, middle orifices, surface orifices and power plants on the formation and change of vortex in front of a dam, and research the operation scheduling and regulation technology for improving the flow field in front of a dam so as to reduce the vortex intensity and eliminate the vortex. This research provides a significant reference for multi-objective design of flood discharge layout and scheduling operation modes of a hydraulic project.

1. OVERVIEW

Vortex is the most common form of fluid movement in front of an intake, and it shows a very complex flow pattern. The vertical vortex often occurs in front of intakes of hydraulic structures such as spillways, diversion pipelines of power station, large-scale water pumps and diversion tunnels. The vertical vortex usually brings certain harm to hydraulic structures and related facilities.

Vortices often appear in front of the intake of hydraulic structures and can be divided into suction vortex and non-suction vortex based on the existence of suction. Vortices can be divided into surface depression vortex, intermittent suction vortex and through suction vortex based on the vortex forms. The suction vortex has a certain destructive effect on hydraulic structures and hydraulic machineries. The destructive effects are shown as follows: 1) The suction vortex suctions the floating objects on water which blocks the passage, reduces the discharge capacity, reduces the efficiency of a power station and endangers the project safety; 2) The suctioned air forms an air bag in the pressure passage, worsens the tunnel flow pattern and increases the fluctuating pressure of the tunnel body; 3) The expansion and contraction of the air bubbles in the water flow during pressure changing reduce the efficiency of hydraulic machinery, generate the noise and cause the vibration and cavitation, resulting in impact on safety of surrounding structures.

Main harms of vertical vortex at gate head in surface orifice are: A. reduce the flow passing capacity; B. cause the structural vibration of the gate pier; C. cause the vibration of the gate.

In this paper, relying on disadvantageous phenomena in practical operation of a large hydraulic project, based on a composite model combined with three research means, i.e. prototype observation of flood discharge, numerical computation and large scale integral hydraulic model, the mechanism and cause of formation of vortex at the gate head with different water levels and gate opening degrees are researched, the vortex characteristics and the impact on gate and pier structures are analyzed, the operation scheduling and control technology to avoid the formation of vortices during operation and the vortex elimination measures are proposed, and suggestions for the operation and management of flood discharge facilities of the power station are made to improve the reliability of safe and stable operation of flood discharge facilities, which provides a significant reference for the multi-objective design of flood discharge layout and scheduling operation mode of a hydraulic project.

2. RESEARCH BACKGROUND

The operation time of flood discharge facilities of a large hydropower station is long every year. The middle orifices and the surface orifices for flood discharge open and close frequently. Take the year 2015 as an example. In 2015, discharge days of Xiangjia Dam was 48, and the discharge volume was 10.773 billion m^3; in total, 170 middle orifice operation orders (for 305 orifices) and 234 surface orifice operation orders (for 432 orifices) were issued; the maximum opening degrees of surface orifice and middle orifice were 6.5m and 3.5m respectively; the maximum discharge flow was 6,410 m^3/s.

The safety of flood discharge facilities is related to the overall operation safety of a dam. In recent years, during operation of spillway surface orifices, the operators of power plants and observers of prototypes found that there were free vortices in gate slot and at gate head to different extents. When the vortex is large, abnormal sound and gate vibration occur. To ensure the safe operation of flood discharge facilities, it is necessary to research the adverse effect of vortex on the operation of hydraulic structures and gates, the formation mechanism of vortex and the vortex elimination measures.

(a) Vortex flow pattern in gate chamber in surface orifice in 2017 (b) Vortex in gate slot in 2015

Figure 1 : Vortex phenomenon in prototype observation.

3. VORTEX MECHANISM AND FORMATION CONDITIONS

It is found from the research that the streamline distribution in front of the dam in the reservoir area of this project has the characteristics of large included angle: The talweg is in the left position of the river course. The angle between Xiangjia Dam body/discharge structure and riverbed is 20° ~ 30°. Besides, the discharge structures are mainly arranged on the right side of the dam. Therefore, the main stream of the whole flow field in front of the dam forms a large angle with each of the flood discharge axis of orifices, and this is an important reason for the occurrence of transverse cross-flow and vortex in front of the gate chamber.

It can be seen from the characteristics of vortex at the gate head and the test data of flow field in upstream water courses and area near the dam that:

(1) The flow of upstream water course conforms to the river direction and forms 30°~ 50° large angles with axis of flood discharge orifice innately.

(2) Most discharge structures are arranged on the right side, which increases the inclined-flow intensity in front of the gate during flood discharging from the gate orifice. In particular, when the surface and middle orifices and power station mainly operate at the right side, the inclined intake flow of surface orifice becomes severer, which enhances the formation of vortex.

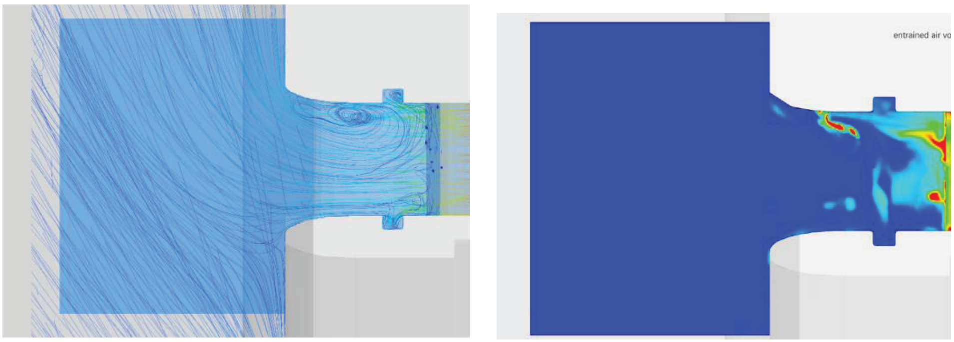


Figure 2 : Research on formation mechanism of vortex at the gate head with numerical model.

(3) The pier of surface orifices is the wide-flat pier connected by small arc. The intake bypass flow phenomenon in front of gate is severer, which intensifies the vortex at the gate head. In contrast, if a streamlined pier with great circle arc is adopted on the left side of 1# gate orifice, the probability of vortex will be greatly reduced.

(4) With the increase of flood discharge flow, the opening height of the gate in surface orifices increases, the submergence of the radial gate decreases, and the vortex intensity increases.

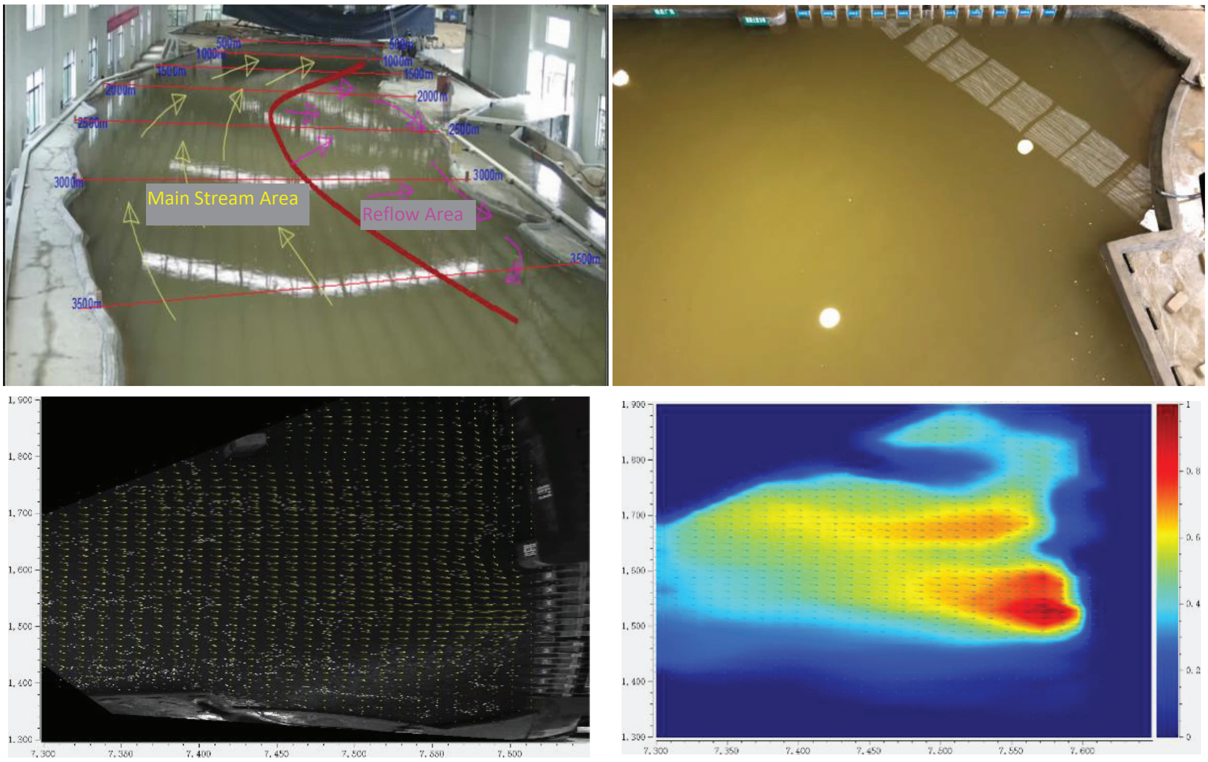


Figure 3 : Analysis of formation conditions of vortex at the gate head with large scale physical model.

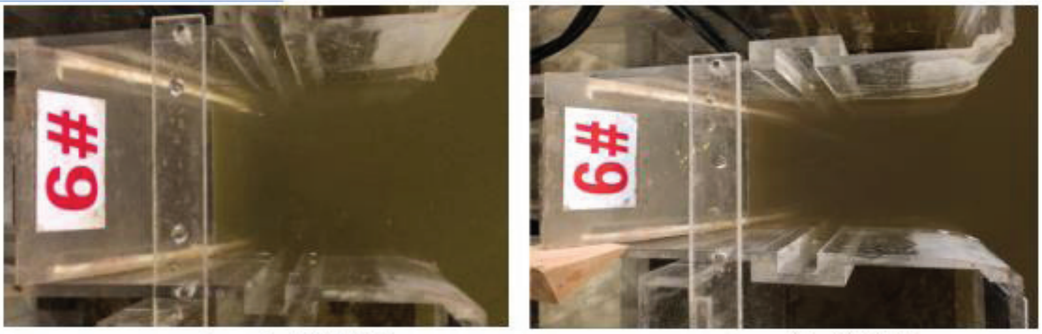
4. IMPACT OF SCHEDULING OPERATION MODE ON VORTEX

Through the reappearance by model test, in the current recommended scheduling mode, the flow pattern at the gate head in surface orifices has the following characteristics:

1. With the increase of the flow, there will be the gradually intensified vortex flow pattern at the gate head in surface orifices and in front of the radial gate. If the flow is 15000m^3/s and below, there is no harmful vortex at the gate head in surface orifice. If the flow is 17500m^3/s and above, since all surface orifices are opened and the opening height of gate in surface orifices is higher than 5.5m, intermittent suction vortex will be generated at the gate head in surface orifices, which may have an adverse impact on the gate and related structures.
2. The vortices at the gate head often appear in the side surface orifices during operation in single area such as surface orifice 2# (the surface orifice 1# has a large arc pier head on the left side. Therefore, the lateral bypass flow is weakened and vortex is not easily formed), surface orifice 6#, 7# and 12#. With the increase of flow, the vortices gradually expand to surface orifice 11#, 10#, 4# and 3#.

Therefore, based on current flood discharge scheduling mode, in order to reduce the frequency and intensity of vortices in front of the gate head, the following principles shall be followed for the scheduling operation of surface orifices: 1. Increase the number of opened surface orifices to reduce the opening height of gates, which weakens the intensity of vortex at the gate head; 2. When all middle orifices are opened, if the surface orifices on the left side are opened in priority, it is not conducive to the formation and development of vortices at the head in surface orifices; 3. If the flow rate is above 15000m^3/s or when all surface orifices and middle orifices are opened for flood discharge, there will be harmful vortices (above type 5) at the gate heads. In order to avoid harmful vortices, some gates in surface orifices shall be fully opened, while other gates in surface orifices shall be opened to a smaller opening degree; alternatively, the opening degree of gates in the middle orifices can be increased and the opening degree of gates in the surface orifices can be reduced.

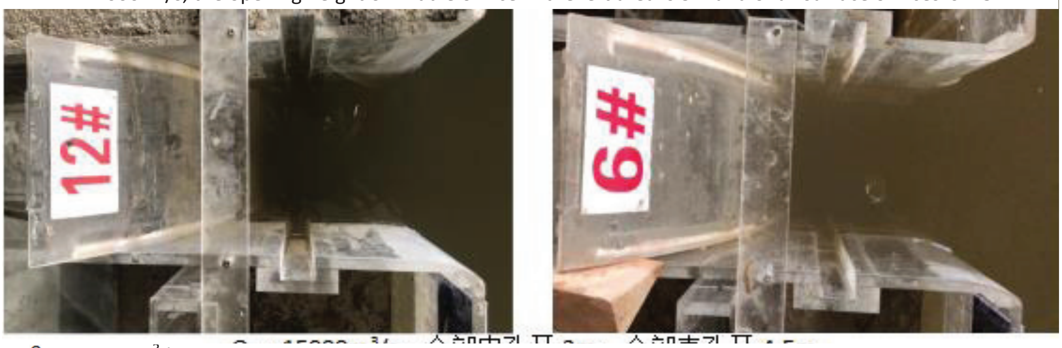
Impact of middle orifice operation mode on vortex characteristics: When more middle orifices shall be opened in case of increase of flow, if the opening height of gates in middle orifices is not higher than 3m, the impact on intake vortex in surface orifices is relatively small no matter when 6 middle orifices in left area or right area are opened or total 12 middle orifices are opened.



Q = 8000m^3/s, the opening height of surface orifice in the left area is 2m

Q =9500m^3/s, the opening height of surface orifice in the left area is 3m

Q =11000m^3/s, the opening height of middle orifice in the left area is 3m and of all surface orifices is 2.5m.



Q =15000m^3/s, the opening height of middle orifice in whole area is 3m and of all surface orifices is 4.5m.

Figure 4 : Reappearance of characteristics of vortex at the gate head with large scale physical model.

Impact of operation modes of left and right power plants on vortex characteristics: If the right power plant is in operation while the left power plant is not in operation, the vortex intensity in intake of the surface orifices will increase; if the left power plant is in operation and the right power plant is not in operation, the vortex intensity in the intake of surface orifices will not change much.

Impact of reservoir water level on vortex characteristics: Take 3m opening height of 10 middle orifices and 4.5m opening height of 12 surface orifices as an example. With the increase of the reservoir water level, the submergence degree of orifice increases, the discharge of orifice also increases and the intensity of vortex in front of gate head in surface orifice has little change.

5. VORTEX REDUCTION AND ELIMINATION MEASURES FOR EXISTING PROJECTS

5.1 Research on optimization of operation and scheduling mode

Under the premise of current scheduling regulations, the characteristics of intake vortex in the surface orifices are as follows: For 8000m^3/s, 6 surface orifices are opened to 2m for control of discharge; for 9500m^3/s, 5 middle orifices are opened to 2m and 6 surface orifices are opened to 3m for control of discharge; for 11000m^3/s, if 5 middle orifices are opened to 3m and 12 surface orifices are opened to 2.5m for control of discharge, there will be harmless vortex (below type 2) in the intake of side surface orifices; for 15000m^3/s, if 10 middle orifices are opened to 3m and 12 surface orifices are opened to 4.5m for control of discharge, there will be object-carrying vortex (type 4) in the intake of side surface orifices; for 17500~20000m^3/s, if 10 middle orifices are opened to 3.5m and 12 surface orifices are opened to 5.5~8m for control of discharge, there will be harmful vortex (type 5~6) in front of intake of most surface orifices; Therefore, in the current flood discharge scheduling scheme, harmful vortices are inevitable when the flow is more than 15000m^3/s. The engineering measures must be taken to reduce its adverse effects.

Based on the flood discharge tests for different scheduling modes, the formation of vortices in front of the gate head in surface orifices is related to the inflow conditions of the river course, the inflow conditions of the gate and the opening height of the gate. In general, if opening the surface orifices and middle orifices in a same area can be avoided, the vortex intensity may be weakened or the probability of vortex formation may be reduced. If the surface orifices in left area are opened in priority, inflow angles in all gates are relatively small and the vortex characteristics will be improved; when the surface orifices in two areas are opened, if the opening height is controlled below 4.5m, there is basically no harmful vortex in front of the gate head.

Besides, on the premise of energy dissipation and shock prevention of stilling basin, the increase of opening height of gates in middle orifices and the reduction of opening height of gates in surface orifices will weaken the vortex intensity in intake of surface orifices.

5.2 Research on project measures

In the model test, the vortex elimination measures such as floating drainage device and pervious pier are explored. When the opening height of gates in surface orifice is lower than 6m, the vortex elimination effect is good; the depth of floating drainage device below water is about 1.0m. As for pervious pier, the head is elliptical, the long half axis is 10m, the short half axis is 3.6m and the underground water depth is 6m. The pervious pier has permeable structure with equal pressure inside and outside the pier so as to ensure the safety of structure and provide the convenient conditions for reconstruction of existing projects.

1# Floating Drainage Device Effect

2# Floating Drainage Device Effect

Pervious Pier Effect

Figure 5 : Comparison of effects of vortex elimination measures.

6. CONCLUSION

(1) Because of large angle between water course in upstream of hydropower station and flood discharge axis of dam, layout of flood discharge facilities and structures of the power station in right bank, shape of gate pier in surface orifices as well as restriction by prevailing flood discharging scheduling regulations, if the reservoir outflow is 15000m^3/s (including flow of power station: 6400 m^3/s and flood discharge flow: 8600 m^3/s) or less, there will be poor vortex to different extents in front of the gate head in surface orifices; if the outflow is higher than 15000m^3/s, there will be intermittent suction harmful vortex. If the unfavorable flood discharge scheduling mode is adopted, the vortex intensity will increase further.

(2) In view of the adverse vibration of the gate caused by the harmful vortex during the prototype observation, in the model test, it is also observed that the harmful vortices can significantly enhance the fluctuating pressure of the flow on the gate plate. Although the fluctuating pressure is not very large and the root mean square of maximum fluctuating pressure of water flow is only 1.2*9.81kPa, the root mean square of the fluctuation is nearly three times larger than that without intale vortex. The main frequency of fluctuating pressure of water flow is 0.5Hz.

(3) On the premise of energy dissipation and shock prevention of stilling basin, the optimization of flood discharge scheduling mode, the operation of orifices in left area, the increase of number of opened surface orifices, the increase of opening height of gates in middle orifices or the decrease of the opening height of gates in surface orifices will weaken the vortex intensity in front of gate head in surface orifices. The combination of floating drainage device, optimal pier and other engineering measures can further weaken or even eliminate the vortex so as to reduce the fluctuating pressure of water flow on gate plate and harmful vibration of gate.

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