Experimental Research on the Conveyance Capacity of a Sluice Project

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Abstract. This paper focuses on the diversion and drainage capacity of a sluice project. In order to study its performance in all operating conditions, we produced a scaled physical model for testing according to related specifications. This test mainly studied the flow, flow pattern and other issues of the sluice under different water level conditions. Through observations and measurements, we obtained a relationship table of water level and flow and found out conditions that should be avoided in actual project. Furthermore, we calculated and analyzed the measured data, and then plotted the relationship figures between the flow coefficient and submergence. These results provide an effective reference for the safe and rational operation of this project.

1. Introduction

The city’s water quality and flood prevention capabilities are one of the foundations for the city’s prosperity and development [1]. The scientific operation and management of the sluice is an important factor for its engineering utility [2][3]. Therefore, it is necessary to conduct a test to simulation and analysis the complex hydraulic characteristics of the sluice in its operating conditions [4][5]. The sluice described in this paper is an important part of a water system renovation project. This overall project is located on an island and close to the core area of a megacity. This whole hydraulic system contains 15 rivers and 3 sluices. This project can effectively improve water quality and urban flood prevention capabilities. The sluice mentioned in this paper connects the Yangtze River and inland rivers and belongs to the level I project. It is mainly a flooding sluice, taking into account drainage during emergency. It operates in coordination with other projects to jointly activate the functions of the island's water system. This sluice plays a very important role in the entire project.

This sluice is located at the western end of the island. Affected by the tide level in the Yangtze River, its flow conditions are more complicated. In this test, we have verified and optimized the theoretical design through the study of the overall hydraulic model test, studied and verified the sluice drainage capacity. Then we provided optimization suggestions for the gate’s position of this sluice.

2. Model design and production

The design and production of the model follow the “Code for normal hydraulics model investigation for hydropower & water resources” (DL/T5244-2010). For the contents not covered by the test
procedure, refer to the “Hydraulic Calculation Manual” and “Model Test Measurement Technology” as well as past related scientific research results and test methods.

According to the test task’s requirements and project’s flow characteristics, the overall hydraulic model should be used for this test.

2.1. Model scales.
The model is designed according to the gravity similarity criterion and adopts a geometric normal model. According to the requirements of the model test and the actual needs, the model linear scale was set to $\lambda = 30$ (prototype: model). The corresponding other physical scale is:

- Velocity scale: $\lambda_v = \lambda^{1/2} = 30^{1/2} = 5.48$
- Flow rate scale: $\lambda_q = \lambda^{5/2} = 30^{5/2} = 4929.5$
- Roughness scale: $\lambda_n = \lambda^{1/6} = 30^{1/6} = 1.76$

The model simulation scope includes some river banks, outer rivers, inlet/outlet, outer stilling pools, inland rivers, sluice chambers, internal stilling pools, etc.

According to the layout plan of the South Ring River Sluice Project, the sluice is located at the western end of the island and is orthogonal to the river embankment. It is affected by tides. The speed of falling is large and may have a significant impact on the operation of the sluice. However, there are about 100m of external rivers on the Yangtze River side of the South Ring River Sluice, which can reduce the influence of tidal rivers on the operation of the sluice. The tidal flows of the Yangtze River will not significantly affect the drainage flow of the sluice, and the main effects are that the inlet and the outside of the river may have a biased flow and return flow. In order to study the outflow status of the sluice to the outlying river, we conducted a moderate simulation of the near-shore current caused by tidal flow on the Yangtze River near the sluice in the experiment. Fig. 1 shows the overall layout of the model.

![Fig. 1. Overall hydraulic model of test](image)

2.2. Model production.
Sluice buildings and gates are made of gray plastic plates. The accuracy of planes and elevations is strictly controlled according to relevant test procedures. The grey plastic plate has a roughness of 0.007 to 0.008. This is converted to a prototype of 0.013 to 0.015 according to a similar theory, which is similar to the concrete roughness.

The river channel and terrain were made of cement mortar. The conventional roughness was 0.02 to 0.0225. The model was carefully dressed with cement powder and fine sand, and the roughness was about 0.011 to 0.012, which could meet similar resistance requirements. The beach on the river bank is located in the water level change area. There may be vegetation growth in alternate wet and dry conditions. The roughness is relatively large. Take the routine as 0.03, and the corresponding model roughness should be about 0.0162. A special treatment was used on the cement surface to make the roughness of about 0.016 ~ 0.017, basically meet the similar requirements of resistance.
2.3. Measurements.
The river water level measuring points are arranged in the middle section of the inner and outer river’s flood prevention troughs.

2.3.1. Flow rate.
In this model, the measuring weir was used to measure flow rate. Each one was set in both internal and outer river.

2.3.2. Water level.
Tracking water level gauges and water level styluses were used to observe the water level simultaneously. These two devices were mutually verified. The former one was collected by computers and the latter one was read manually. The accuracy of the styluses could less than 0.1 mm. Each stylus reference elevation was carefully calibrated and further corrected using the static water connection method to eliminate minor errors in the reference elevation between the stylus probes.

2.3.3. Velocity.
The flow velocity was measured with opto-electronic flow meters. Data was collected by computers and up to 48 points’ velocities could be measured at the same time.

2.3.4. Flow pattern.
Tracers were dropped into the flow field to facilitate observation of flow field. High-performance cameras were used to record flow field images for analysis.

3. Results

3.1. Weir flow.
In this test, both the characteristic water level of inland river and the water level of outer river under the designed conditions were observed. The flow rates through the sluice between the inland river and the outer river were also recorded. The measured data of each test condition are listed in the table 1.

| Inland river (m) | Outer river (m) | Flow rate (m³/s) | Function |
|------------------|------------------|------------------|----------|
| 2.3              | 2.358            | 120              | diversion|
| 2.2              | 2.26             | 120              |          |
| 1.7              | 1.782            | 120              |          |
| 1.5              | 1.602            | 120              |          |
| 2.07             | 2.15             | 120              |          |
| 2.05             | 2.15             | 140              |          |
| 2.3              | 2.38             | 140              |          |
| 2.3              | 2.438            | 180              |          |
| 2.3              | 2.548            | 240              |          |
| 2.7              | 2.642            | 120              |          |
| 2.7              | 2.58             | 192              |          |
| 2.218            | 2.15             | 120              | drainage |
| 2.31             | 2.15             | 192              |          |
| 2.7              | 0.92             | 294              |          |
Seen from the data in Table 1, when the inland water level is kept at 2.30m and the water level at the river reached 2.358m, the flow rate of the sluice can reach 120m³/s. When the river level rises to 2.38m/2.438m/2.548m, sluice’s diversion flow rate increases up to 140/180/240m³/s. The water level in the outer river is still lower than 3.38m, the average high tide level in the outer river. It shows that the gate can meet design requirements and has a large margin. It also shows that when the river water level exceeds 2.38m, the gate should be used to control the diversion flow so as to avoid excessive flow that may cause inland river’s flushing.

When the water level of the inland river is 2.7m and the discharge flow is 120/192m³/s, the measured water level of outer river is 2.642/2.58m. Therefore, when the outer river’s water level is less than 2.58m, the discharge flow should be controlled through the gate. Under the operating condition of 2.7m in inland river and averaged 0.92m in outer river, the flow rate reaches 294m³/s so that the energy dissipator cannot meet the design requirements. Caused more serious scouring, it is recommended to avoid running under this condition.

Weir flow coefficient. According to the measured water level and flow rate of inland and outer rivers, the flow coefficients and the submergence degrees can be calculated by the formula

$$Q = mB\sqrt{2gH_0^{1.5}}$$

The relationship between them is plotted in Figure 3-1, where the upstream water head above the sluice bottom plate containing the flow velocity head and the downstream head above the sluice bottom plate. Operation can be based on internal and external river water level calculations; find m, find out the gate flow.

According to the analysis of test data, the relationships between weir flow coefficient and submergence degree are very close under the two operating modes of diversion and drainage. To facilitate the application, we plotted the test data of the two modes of operation in the same figure.

![Fig. 2. curve of flow coefficient ~ submerged degrees of weir flow](image)

3.2. Orifice flow.
Free orifice flow. When the downstream water level does not affect the flow rate through the sluice, the orifice flow is a free orifice flow. According to formula

$$Q = \mu Be\sqrt{2gH_0}$$

the flow coefficients of the free orifice flow can be calculated and the relationship between $\mu$ and $e/H_0$ are plotted in Figure 3-2. In this formula, $e$ is the gate opening height and $H_0$ is the upstream water head above the sluice bottom plate. Based on test data, the approximate calculation formula for the flow coefficient is

$$\mu = 0.618 - 0.232e/H_0.$$
Submerged orifice flow. When the downstream water level is high enough to affect the sluice flow rate, there is submerged orifice flow. The flow coefficients $\mu_s$ of the submerged hole can be calculated by the formula $Q = \mu_s Bh \sqrt{2gh_s(H_0-h_s)}$ and the curve $\mu_s \sim h_s/e$ are plotted in Figure 3-3. In this formula, $e$ is the opening height of the gate. $h_s/H_0$ is the downstream/upstream water head above the sluice bottom plate. According to the test data, the approximate calculation formula is $\mu_s = 1.151(h_s/e)^{-1.33}$.

Critical Free orifice flow. During the test, the gate opening height and flow rate were fixed to obtain a stable inland water level under free-hole flow conditions. There is the critical free orifice flow when the river level of the outer river rises to affect the flow rate through the sluice (causing the rise of the upstream water level). In the critical point, the highest outer river’s water level in condition of maintaining the free flow, the relationship between relative height $e/H_0$ and relative submergence height is plotted in Figure 4. The curve’s left / right side is the zone of free orifice flow / submerged orifice flow. In actual operation, the flow pattern of orifice can be discriminated by this figure and then select the right formula to calculate the flow rate. It should be noted that the demarcation point between the free orifice flow and the submerged orifice flow is not a very stable value. Under the same water level and opening degree conditions, certain changes may occur due to the influence of gate operation mode and flow pattern. Different $H$, $e$ and $h_s$ can form the same $e/H_0$ and $h_s/H_0$. The critical point can also change.
4. Conclusions
We set up a reasonable proportion of the physical model for experimental study to verify the conveyance capacity of a sluice in designed conditions. The research results show that the conveyance capacity basically meets the designed requirements. In order to ensure the energy dissipator works effectively, the operator should avoid the conditions that the flow exceeds 140m$^3$/s in Table 1. Moreover, the flow pattern of weir flow, free orifice flow, submerged orifice flow and critical orifice flow were studied in this test. The relationship curves between the flow coefficient and submergence were plotted, which provided a scientific basis for the safe and effective operation of this sluice project.

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