Experimental study on head loss coefficients of tailrace surge tank for Baihetan hydropower station

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Abstract: The scale and hydraulic inertia of the tailrace surge tank of Baihetan hydropower station are huge. Its resistance characteristics are directly related to the accuracy of the calculation results of the hydraulic transient process, the stability of the unit operation, the economy and safety of the project. The influence of split ratio, cross-sectional area of the restricted orifice and unit operation on the head loss coefficient of Baihetan surge tank was studied by model experiment method. The results show that the head loss coefficient increases with the increase of split ratio and decreases with the increase of the cross-sectional area of the restricted orifice. Under the diffluence condition, the head loss coefficient of the restricted orifice in double unit operation is obviously larger than that in single unit operation. Under the confluence condition, the head loss coefficients of the restricted orifice in single and double unit operation are the same. The deviation will be large when using the recommended value in the specification, the experimental results are more reasonable. The research conclusions will provide technical support for the design and operation of Baihetan hydropower station as well as reference for similar projects.

1. Introduction
Baihetan hydropower project is located on Jinsha River, of which the underground powerhouse is set at the head of the water diffluence system. The gross installed capacity of this station is 16 000 MW. There are four hydraulic units arranged on the left and right banks respectively, totally 16 single unit 1 000 MW Francis type water turbine-generator units, and the rated flow is 547.8 m³/s. For the headrace tunnel, one unit uses one tunnel, and for the tailrace tunnel, two units share one tunnel and one tailrace surge tank.

The form of Baihetan surge tank is cylindrical throttled surge tank with double restricted orifices. It is the largest underground surge tank in the world, of which the diameter of the surge tank is 43m – 48m, and the maximum height exceeds 100 m. Two circular restricted orifices with a diameter of 7.6m are arranged on the upstream side of the restricted orifice plate, at the bottom of which a split piers is arranged in the flow passage with a height of 18m. The typical structural arrangement of the surge tank is as shown in figure 1.
The resistance characteristics of the tailrace surge tank have significant influence on the amplitude and attenuation of the surge, safety of water conveyance system, stability of power generation and water hammer reflection effect [1]. Therefore, in the calculation of hydraulic transient process, determination of the resistance loss coefficient of surge tank is the key, which is usually obtained based on relevant codes and manuals for small and medium sized projects [2]. In Baitetan hydraulic project, due to the factors of huge scale of surge tank, double restricted orifices, and the interaction of flow at the junction of draft tube and draft tunnel. The deviation will be large when using the value recommended in the specification. In view of this, the hydraulic model experiment method is used in this paper to study the water head loss coefficient of the tailrace surge tank shared by two units, which can provide a basis for accurate calculation of hydraulic transient process of the water conveyance system as well as a reference for the design and research of other similar projects.

2. Model experiment

2.1. Experimental model
The No. 6 tailrace surge tank on the right bank where No.11 and No.12 units are located is taken as the research object. The experimental model is designed according to gravity similarity criterion, and a normal model with the scale of 1:40 is adopted. Simulation scope: the simulated length of the draft tube of No.11 and No.12 is 182m and 150m respectively, and that of the tailrace tunnel is 200m, which is more than 10 times of the tunnel diameter. The simulated range of the surge tank is from the bottom to the top. Experimental model layout is as shown in figure 2. The experimental model is made of PMMA (polymethyl methacrylate) and the auxiliary pipe is made of PVC plastic pipe. The model is shown in figure 3.

In the experiment, orifice flowmeter was used to measure the flow of draft tube, and triangle measuring weir was used to measure the flow of tailrace tunnel. In order to measure the head loss coefficient at the bottom of the surge tank and when the water flows into and out of the tailrace surge tank (hereinafter referred to as diffuence flow and confluence flow), four pressure measuring sections from 1-1 to 4-4 were arranged on the experimental model, as shown in figure 2. The pressure measuring section of draft tube and tailrace tunnel is located three times the tunnel diameter from the surge tank, and that of the surge tank is located one time the surge tank diameter from the bottom. Four pressure taps are arranged equidistant along the circumference of the tunnel section in each measuring section. They are connected to the piezometer to measure the piezometric head on the corresponding section.
2.2. Experimental scheme

2.2.1. Experimental conditions

According to the specification, the cross-sectional area of the restricted orifice should be 25% - 45% of the section area of the draft tube or tailrace tunnel [3]. In this experiment, three restricted orifice schemes are selected for the study, as shown in table 1. For each restricted orifice scheme, the head loss was measured for conditions of water flowing into and out of the surge tank respectively, and the corresponding head loss coefficient was calculated and analyzed. Water flowing into and out of the

Figure 2. Experimental model and layout of measuring section.

Figure 3. Experimental model.
surge tank is called the diffluence pattern and the confluence pattern respectively [4-6]. Schematic diagrams of the diffluence pattern and the confluence pattern are as shown in figure 4. In Baihetan hydropower project, one surge tank with double restricted orifices is shared by two units, so each flow pattern includes conditions of single and double unit operation.

Flow pattern simulation and flow control are realized by switching the valves on the draft tube and tailrace tunnel. For each experimental point, the flow and piezometric head are measured when the flow pattern is stable. Steady-state tests with different split ratios are used to simulate the dynamic flow process of the surge tank.

| Scheme | Restricted orifice diameter D/m | Area ratio a to surge tank/% | Area ratio to tailrace tunnel/% | Area ratio to draft tube/% |
|--------|--------------------------------|-----------------------------|-------------------------------|---------------------------|
| 1      | 7.3                            | 8.7                         | 34.4                          | 19.7                      |
| 2      | 7.6                            | 9.4                         | 37.3                          | 21.3                      |
| 3      | 8.3                            | 11.2                        | 44.5                          | 25.5                      |

* For the area ratio calculation in the table, the area of the restricted orifices refers to the total area of the two holes, and the area of the draft tube refers to the total area of the two branch tunnels.

2.2.2. Head loss calculation formula

According to the energy equation, the formula of head loss between adjacent sections is

$$\Delta h_{ij} = (Z_i + \frac{P_i}{\gamma} + \frac{V_i^2}{2g}) - (Z_j + \frac{P_j}{\gamma} + \frac{V_j^2}{2g})$$

In which, $Z$ is the section elevation, m; $P/\gamma$ is the pressure head, m and $V/2g$ is the velocity head, m. Subscript $i$ and $j$ represent the measuring section.

The calculation formula for head loss coefficient between adjacent sections is

$$\xi_{ij} = \Delta h_{ij} / \frac{V^2}{2g}$$

In which, $V$ is the characteristic velocity, m/s. Under the diffluence condition, the characteristic velocity is the flow velocity in draft tube, and under the confluence condition, that is the flow velocity in tailrace tunnel.

3. Experimental results

3.1. Diffluence condition

Under the diffluence condition, the head loss coefficient variation trend of each restricted orifice scheme is shown in figure 5. The split ratio $q = Q_4 / (Q_1 + Q_2)$ ($Q$ represents the flow rate of each section, and the subscript indicates the section position) on the abscissa axis refers to the ratio of the flow into surge tank to the total flow of the two draft tubes. It can be seen that under unsteady flow state, besides the size of the restricted orifice, the head loss coefficient of water flowing into the surge tank is also related to the split ratio and unit operation.
The head loss coefficient of the restricted orifice decreases with the increase of cross-sectional area of the restricted orifice and increases with the increase of split ratio. When the split ratio is 1, all water flows into the surge tank, and the head loss coefficient is the largest, which is 13.32, 11.77 and 8.66 respectively in single unit operation and 53.02, 47.39 and 33.21 respectively in double unit operation. The head loss coefficient of double unit operation is obviously greater than that of single unit operation. The main reason is that the draft tubes are connected at the bottom of the surge tank, when the single unit is running, the water can flow into the surge tank from two restricted orifices, which is equivalent to doubling the area of the resistance area.

![Figure 5. Variation trend of head loss coefficient under diffusion condition.](image)

### 3.2. Confluence condition

The variation trend of head loss coefficient of each restricted orifice scheme under the confluence condition is shown in figure 6. The split ratio $q = Q_4/Q_3$ on the abscissa axis refers to the ratio of the flow out of surge tank to the flow of the tailrace tunnel. It can be seen that different from the condition of flowing into the surge tank, the variation trend of head loss coefficient has no relevance to the unit operation.

The head loss coefficient of the restricted orifice also decreases with the increase of cross-sectional area of the restricted orifice and increases with the increase of split ratio. When the split ratio is 1, all water flows into the surge tank, and the head loss coefficient is the largest, which is 16.05, 13.22 and 9.42 respectively in single unit operation and 16.35, 13.40 and 9.42 respectively in double unit operation. With the same restricted orifice scheme, the resistance coefficients are nearly the same for both single and double unit operation. The reason is that water flows out of the surge tank from both two restricted orifices whether in single or double unit operation.

![Figure 6. Variation trend of head loss coefficient under confluence condition.](image)
4. Analysis of head loss coefficient

4.1. Flow coefficient analysis for restricted orifice

According to the Design Specification for Surge tank of Hydropower Station (NB T35021-2014), the head loss of restricted orifice \( h_c \) can be approximately calculated by the formula

\[
h_c = \frac{1}{2g} \cdot \left( \frac{Q}{\phi S} \right)^2,
\]

where \( \phi \) represents the flow coefficient of resistance, which can be taken as \( 0.6 - 0.8 \), \( S \) represents the section area of the restricted orifice and \( Q \) represents the flow into and out of the surge tank. The flow coefficient calculated from the head loss coefficient obtained from the above formula and experiment, it can be seen that when the split ratio is small, the recommended flow coefficient is inconsistent with the measured value. While when the split ratio is 1, the flow coefficient of water flowing into the surge tank is between 0.67 - 0.68, and that of water flowing out of the surge tank is between 0.73 – 0.74, which are within the range of the recommended value in the specification, as shown in table 2. The above analysis shows that the flow coefficient recommended in the specification is the maximum resistance coefficient, and the head loss characteristics of the surge tank of Baihetan hydropower station conforms to the general law.

In the calculation and analysis of hydraulic transient process, the flow coefficient of restricted orifice obtained by experiment is more in line with the actual situation of Baihetan hydropower station than that recommended in the specification. The data comparison in table 2 shows that the difference of head loss coefficient between each scheme is large, but that of the flow coefficient is small, so the deviation of the recommended method in the specification will be large. Considering from the perspective of economy and safety, model experiment is recommended for large-scale projects.

Furthermore, according to the head loss coefficient and flow coefficient obtained by the experiment, we can know that the head loss of water flowing into the surge tank is greater than that flowing out of the surge tank, showing the general rule of “easy to flow out, hard to flow in”. The reason is that the diffusion degree of the flow passage of water flowing from the tailrace tunnel into the surge tank is greater than that of the reverse situation.

Table 2. Table of corresponding flow coefficients of head loss in different conditions.

| Unit operating | Scheme | Divergence condition | Confluence condition |
|---------------|--------|---------------------|---------------------|
|               |        | Head loss coefficient \( \xi \) | Flow coefficient \( \phi \) | Head loss coefficient \( \xi \) | Flow coefficient \( \phi \) |
| Single unit   | 1      | 13.32 | 0.68 | 16.05 | 0.73 |
|               | 2      | 11.77 | 0.68 | 13.22 | 0.74 |
|               | 3      | 8.66  | 0.67 | 9.42  | 0.74 |
|               | 1      | 53.02 | 0.68 | 16.35 | 0.73 |
|               | 2      | 47.39 | 0.68 | 13.4  | 0.74 |
|               | 3      | 33.21 | 0.68 | 9.42  | 0.74 |

4.2. Fitting formula of dynamic head loss coefficient

For ease of application of computer calculation, a quadratic regression analysis is conducted with the principle of least square method on the relationship between the head loss coefficient and the split ratio obtained by the experiment [7-8], obtaining the formula of the head loss coefficient as shown in table 2. It’s hard to judge which scheme is better by the experimental results of the three restricted orifice schemes. However, after the calculation and analysis of transient process of water conveyance and power generation system with the head loss coefficient of the restricted orifice obtained by the experiment, Scheme 2 is selected for Baihetan hydropower station.
Table 3. The formula of the head loss coefficient.

| Unit operating | Scheme | Head loss coefficient under diffuence condition | Head loss coefficient under confluence condition |
|----------------|--------|-------------------------------------------------|-------------------------------------------------|
| Singles unit   | 1      | $\xi_{14} = 10.51q^2 + 1.3182q + 1.4447$       | $\xi_{43} = 16.713q^2 + 0.2803q - 1.0118$        |
|                | 2      | $\xi_{14} = 9.051q^2 + 1.1782q + 1.5579$       | $\xi_{43} = 13.48q^2 + 0.6463q - 1.134$         |
|                | 3      | $\xi_{14} = 6.3853q^2 + 0.5733q + 1.6621$      | $\xi_{43} = 8.7059q^2 + 1.689q - 1.1437$        |
| Double unit    | 1      | $\xi_{14} = 36.567q^2 + 17.777q + 0.2322$      | $\xi_{43} = 19.034q^2 - 3.1703q + 0.0273$       |
|                | 2      | $\xi_{14} = 36.569q^2 + 10.462q + 1.0409$      | $\xi_{43} = 15.178q^2 - 2.2055q + 0.2022$       |
|                | 3      | $\xi_{14} = 21.798q^2 + 10.86q + 0.8381$       | $\xi_{43} = 10.575q^2 - 1.5535q + 0.0916$       |

5. Conclusion

In this paper, the head loss coefficient of throttled tailrace surge tank in Baihetan hydropower station is obtained by model experiment. The results show that the head loss coefficient decreases with the increase of cross-sectional area of the restricted orifice and increases with the increase of split ratio. Under diffuence condition, the head loss coefficient in double unit operation is obviously greater than that in single unit operation. Under confluence condition, the head loss coefficients are the same in both single and double unit operation.

Analysis of flow coefficient of the restricted orifice shows that when the split ratio is 1, the restricted orifice flow coefficient of the surge tank in Baihetan hydropower station is within the recommended value range, proving that the head loss characteristics of the surge tank in Baihetan hydropower station conform to the general law. However, the deviation of the value recommended in the specification is relatively large. From the perspective of economy and safety, it is recommended to use the model experiment to determine the value for large-scale projects.

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