Research on Hydraulic Characteristics of Navigable Tunnels of High-DamNavigable Structures and Ship Navigation Test

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Abstract. To deal with the problem of ship navigation under the ultra-small section coefficient of navigable tunnels of high dam navigation structures, a large-scale hydraulic physical model combined with a self-propelled ship model was used to study the characteristics of the unsteady flow of the tunnel discharge and the navigation parameters of ships at different speeds. This paper analysed the influence of the ship lock discharge on the tunnel water level fluctuation and flow velocity, proposed parameters such as the size of the navigable tunnel for 1,000-ton ships, the recommended speed and the amount of ship sinking, which provide references for the design of navigable tunnels for high-grade waterways.

1. Introduction
High-dam [1] navigable buildings mainly include two types of multi-level ship locks and ship lifts [2], which are connected through intermediate channels. However, high-head hydro-electric dams are generally built between mountains and valleys. Due to topographical restrictions, intermediate channels often need to pass through mountains and take the form of navigable tunnels. As a special restricted channel, the navigation tunnel is restricted by geological and economic conditions. And the width of the channel often cannot meet the requirements of relevant standards or regulations. However, there are few studies on navigable tunnels at home and abroad, and the related research results are mainly for small navigable ships, only 300-500 tons, which cannot meet the needs of large-scale navigable ships in high dams [3].

The ship’s cross-shore speed, subsidence, rudder angle, and tunnel hydraulic characteristics in the navigation tunnel affect the safety and efficiency of the ship's navigation [4-6]. These ship navigation elements are closely related to the cross-sectional scale of the navigation tunnel. Relying on the 1,000 t navigable tunnel project of the second line of Wujiang Shatuo Hydropower Station, this research focused on the impact of the use of the navigation tunnel in the ship lock on the water flow conditions of the navigation tunnel and hydraulic characteristics of large-scale ships navigating in navigable tunnels, which provide technical support for the design of high-level navigation tunnels.

2. Project Overview
Shatuo Hydropower Station is located at about 7 km upstream of Yanhe County in the northeast of Guizhou Province. The hub consists of a concrete gravity dam, overflow surface holes on the dam, water intake section on the left bank, powerhouse behind the dam and navigational buildings on the right bank. As the main building of the Shatuo Hydropower Station has already occupied the river course, there is no condition to arrange the second-line navigable buildings in the river course, so the second-line navigable buildings are arranged in the mountain on the right bank (Figure 1).
The navigable buildings on the second line of Shatuo Hydropower Station adopt a two-level navigable structure scheme of ship lock and ship lift, which are connected by a navigable tunnel. The effective width of the tunnel water is 16 m, the water depth is 5.5 m, while the navigable clearance is not less than 10 m, with the total length of navigable tunnel at 287 m (Figure 2).

Figure 1. Layout of navigable buildings on the second line of Shatuo Hydropower Station.

Figure 2. Layout of the navigable tunnels of the Shatuo Line 2 navigable buildings.

3. Model Design

3.1 Design of Physical Model of Navigation Tunnel

According to the test task, considering the total water balance of the navigable tunnel, the simulation scope of the model includes the entire navigable tunnel section and the upstream and downstream approach channel sections. The tunnel has a net width of 16 m and a water depth of 5.5 m, which concludes from the upstream to ship lock exit and from downstream to the entrance of the downstream ship lift cabin. The model is designed as normal according to the gravity similarity criterion, with the scale at 1:20.

Geometric similarity: \( \lambda_L = \lambda_{H1} = \frac{L_p}{L_m} = 20 \)

Where, \( \lambda_L \) is Plane scale. \( \lambda_{H1} \) is Vertical scale. \( L_p \) is the length of the prototype. \( L_m \) is the length of the model.

Flow Rate Similarity: \( \lambda_q = \lambda_{L1}^{1/2} = 4.472 \)

Where, \( \lambda_q \) is the flow rate scale.

Resistance Similarity: \( \lambda_n = \lambda_{L1}^{16} = 1.6475 \)

Where, \( \lambda_n \) is roughness coefficient scale.
The original channel of the navigation tunnel is made of concrete, and the roughness is between 0.015 and 0.017, converted to the model at about 0.01. In order to ensure the similar roughness, the inner wall of the tunnel is made of smooth plastic plates, whose roughness can meet the test requirements.

3.2 Ship Model Design
The ship model and the hydraulic model are designed to be geometrically normal, with the scale at 1:20.

Draft scale is $\lambda_T = \lambda_l = 20$. Displacement scale is $\lambda_D = \lambda_l^3 = 8000$. Speed scale is $\lambda_q = \lambda_l^{1/2} = 4.472$. Time scale is $\lambda_T = \lambda_l^{1/2} = 4.472$. Area scale is $\lambda_A = \lambda_l^2 = 400$. Scale of volume, weight, mass and force is $\lambda_{(V, \, G, \, M, \, F)} = \lambda_l^3 = 8000$.

4. Analysis of test results

4.1 The Characteristics of Unsteady Flow in tunnels

4.1.1 Unsteady Flow Process of Ship Lock Discharge
The highest navigable water level of the upper reaches of the Shatuo Junction is 365 m, while the design water level of the tunnel is 353.5 m, with the difference of water head at 11.5 m. The Q-t process of discharge flow rate of the ship lock (Figure 3) is provided by the ship lock hydraulic test.

![Figure 3. the Q-t process of discharge flow rate of the ship lock.](image)

4.1.2 Water Level
The first one is tunnel section. After the ship lock discharge begins, the water level in the tunnel begins to rise (Figure 4), with the maximum water level raised by 0.42 m and the maximum water level fluctuation less than 0.2 m. The water level basically drops to within 0.2 m after the completion of discharge within 3 minutes, without obvious fluctuated the water level. However, the maximum elevation of the water level is less than 0.25 m at the exit of the tunnel, with the fluctuation less than 0.1 m.

The second one is open channel section (Figure 5). The water level fluctuation of the open channel section is significantly smaller than that of the tunnel section. The maximum water level fluctuation caused by the ship lock discharge is less than 0.1 m. The maximum water level in front of the ship lift lock on the right is raised by 0.37 m, while the left one is raised by 0.26 m.
4.1.3 Flow Rate
When the water is discharged, the maximum flow velocity in the tunnel is about 0.9 m/s (Figure 6). With the decrease of the discharge flow, the water velocity in the tunnel decreases rapidly. After the discharge is completed, the flow velocity in the tunnel decreases to 0.15 m/s or less. After the lower gate of the ship lock is open, the flow velocity in the tunnel is reduced to within 0.1 m/s, which basically has no effect on the navigation of the ship.

4.2 Ship Sailing Test
4.2.1 Cross-Shore Speed
The ship is moving in a restricted channel, and the water flow is affected by the boundary conditions to produce a blocking effect, forming a water level difference before and after the ship, and a backflow around the ship. The ship is moving in a restricted channel, and the water flow is affected by the boundary conditions to produce a blocking effect, forming a water level difference before and after the ship, and a backflow around the ship. The ship's cross-shore speed $V$ decreases. The cross-shore speed is the main parameter for calculating the navigable tunnel's passing capacity. The relationship between the speed $V_0$ of the ship model in open water and the speed $V$ on the opposite shore in the tunnel with the same main engine power (Figure 7) can be fitted as:

$$
V = 0.8764 \ln(V_0) + 0.7896
$$

(1)
Figure 7. Relationship between $V$ and $V_0$.

The cross-section coefficient of the Shatuo navigation tunnel is 3.47. The speed reduction of ships in the tunnel on the other side is between 21% and 30%, and the ratio of $V_0$ to $V$ is logarithmic, indicating that as the speed increases, the drag acceleration increases.

4.2.2 Ship Sinking

When a ship is navigating in a tunnel, the water movement is limited not only by the depth of the water but also by the width of the water area. The speed of the water flowing through the hull increases, the pressure changes along the length of the ship increases. The hull floating change intensifies, the sinking volume of the ship increases. From the relationship between $V_0$ and $D$ (Figure 8), it can be seen that the ratio between the rate of fixed speed $V_0$ and the sinking amount $D$ of the ship is exponential, which can be fitted as follows:

$$D = 3.1299e^{0.9349V_0}$$

4.2.3 Ship Operations

Due to the arc-shaped layout of the tunnel and the 16 m width of the tunnel, the ship needs to continuously adjust the course with a larger rudder angle when navigating in the tunnel. When the ship moves up (Figure 9), the rudder angle is large at the entrance of the tunnel, below the bend and near the approach channel of the ship lock. When the ship descends (Figure 10), the rudder angle is relatively large near the lower approach channel and the tunnel crest and near the exits the ship lock. On the whole, the ship's downward operation is better than that of the upward direction. From the perspective of ship operation, when the ship is running in the tunnel, the speed is not easy to be too high or too low. The ship needs to adjust the course with a larger rudder angle amid slow speed and...
relatively poor steerage. When $V_0<1.0$ m/s, the maximum rudder angle exceeds 30°, when $1.0\ \text{m/s} \leq V_0 \leq 1.5$ m/s, the ship is in good operation conditions, with the rudder angle basically less than 25°, and when $V_0>1.5$ m/s, it is more difficult to operate the ship, and the probability of collision with the side wall is obviously increased. Judging from the actual ship operation and rudder angle distribution map, it is recommended that the opposite shore speed should be kept at about 1.0 m/s, when the ship navigates in the Shatuo navigation tunnel.

![Figure 9. the ascending course chart of $V_0=1.2$ m/s ship](image)

![Figure 10. the descending course chart of $V_0=1.2$ m/s ship](image)

5. Conclusion

The length of the Shatuo tunnel is relatively short. The use of the tunnel to discharge water causes the water level in the tunnel to rise rather than form an oscillating wave in the tunnel [7]. The water level basically drops to within 0.2 m after 3-minute water discharging, which can meet the working water level requirements of the ship lift. The maximum flow velocity in the tunnel is about 1.0 m/s when the water is discharged. It quickly decreases to below 0.15 m/s after the completion of water discharging, which basically has no effect on the navigation of the ship.

When the bending radius of the navigation tunnel is not less than 800 m, the effective cross-sectional width of the tunnel is 16 m, the water depth is 5.5 m, and the cross-sectional coefficient is not less than 3.5, 1000t-class ships can pass the tunnel smoothly, with recommended opposite shore speed at $V=1.0$ m/s, the rudder angle basically less than 25° and the sinking amount of the ship less than 15 cm, which can provide a reference for the design of navigation tunnels for high-grade waterways.
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