Analysis of hydraulic characteristics of double-layer inlet

Jiyang Sun[1,a], Bin Wu[2,b], Mengzhen Zhang[1,c], Ming Chen[2,d] and Qingsheng Chen[1,e*]

[1]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China
[2] East China Hydropower Survey and Design Institute of China Electric Power Construction, Hangzhou, China

[a]email: 1550479467@qq.com, [b]email:wu_b@hdec.com,
[c]email:chen_m5@hdec.com, [d]email:1308078053@qq.com,
*[e]Corresponding author's e-mail: qschen-dragon@163.com

Abstract. Based on the relevant design parameters of the storage power station diversion tunnel, a numerical simulation study was conducted using the VOF hydrodynamic model to investigate the arrangement of the double-layer inlet, relative pressure and head loss coefficient. By varying the ratio of the horizontal tunnel area to the vertical shaft inlet area, an analysis of the double-layer inlet diversion tunnel was performed in terms of relative flow rates, flow Froude numbers, The research results indicate that during the discharge of the double-layer inlet, the flow is mainly controlled by the discharge from the vertical shaft and is influenced by the downstream flood discharge tunnel section. Changes in the area ratio have a relatively small impact on the flow distribution of the double-layer inlet and have no effect on the velocity distribution and pressure.

Keywords: double-layer discharge; inlet; diversion tunnel; hydraulic characteristics

1 Introduction

In hydraulic and hydroelectric engineering, the greatest advantage of configuring diversion tunnels as a combination of horizontal tunnels and vertical shaft inlets lies in their ability to use the vertical shaft as the inlet for discharge during the operational phase, while also serving as a conduit for floodwater during construction. This approach not only reduces the height of cofferdams required during construction but also shortens the construction period, thereby facilitating the project's rapid realization of its intended benefits. Previous research on diversion tunnel inlet structures mainly focused on single-layer horizontal tunnels or vertical shafts. Liu, T. [1] ensured the construction safety of the diversion tunnel at the Xiluodu Hydropower Station and conducted a study on the operation of the horizontal inflow port. Duan, W. [2] and others investigated the vortex patterns that occur by changing the type of horizontal inflow port and proposed vortex elimination solutions. Yan, X. [3] and others conducted numerical calculations using the VOF method to study the critical water level at which air-entraining vortices

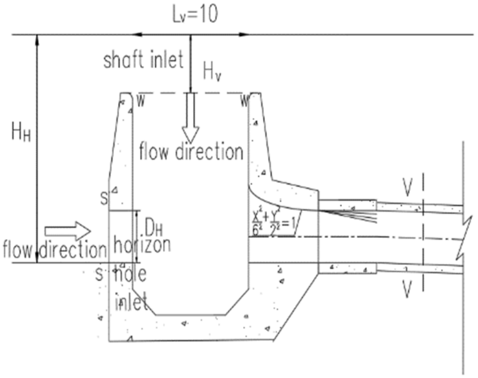
D. Li et al. (eds.), *Proceedings of the 2023 9th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2023)*, Advances in Engineering Research 228,
https://doi.org/10.2991/978-94-6463-336-8_62

are generated at the entrance of horizontal tunnels. Aydin, M.C. [4] and others found that compared to traditional vertical shaft spillways, the new design of vertical shaft spillways exhibits better discharge capacity under the same head. Kabiri-Samani, A. [5] and colleagues studied the hydraulic characteristics of vertical shaft spillways with innovative entrances, including the head-discharge relationship, discharge coefficient, and critical submergence depth. They derived empirical equations related to critical submergence depth and discharge coefficient, which are applicable to different flow conditions with Marguerite-shaped entrances. Ye, X. [6] and others, using a combined approach of physical model experiments and numerical simulations, optimized the design of vertical shaft inlets, effectively improving weir crest flow patterns, reducing inlet water level fluctuations, and increasing discharge capacity.

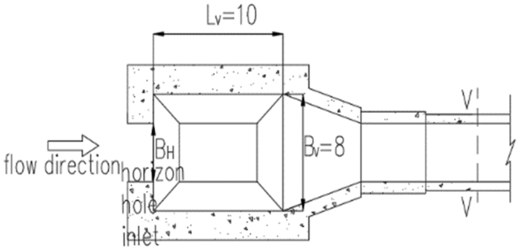
The double-layer inflow port, as a new arrangement method, exhibits a more complex flow pattern within it due to the mutual interaction between the horizontal tunnel and the vertical shaft inflow. This paper intends to use numerical simulation as a research method to study and analyze the hydraulic characteristics of the double-layer inflow port's flow pattern by varying the ratio of the area between the horizontal tunnel and the vertical shaft inlet. The goal is to provide guidance for the design based on the flow characteristics.

2 Model research scope and grid division

The double-layer intake layout of the diversion tunnel of a hydropower station reservoir construction is shown in Figure 1. The inlet of the horizontal tunnel is a rectangular section of $B_H \times D_H$; the shaft inlet is a rectangular section of $B_v \times L_v$ (8 m × 10 m). The simulation range of this paper includes the reservoir area, inlet, tunnel section and outlet. In the study, the reservoir area is simplified as a rectangular water body of 40 m × 18 m × 35 m ($L \times W \times H$), and the downstream extends 18 m after the sudden expansion section of the outlet to ensure the free flow of water. The calculation domain is shown in Figure 2.



(a) Vertical section diagram



(b)Horizontal profile

Fig. 1. Double inlet layout diagram

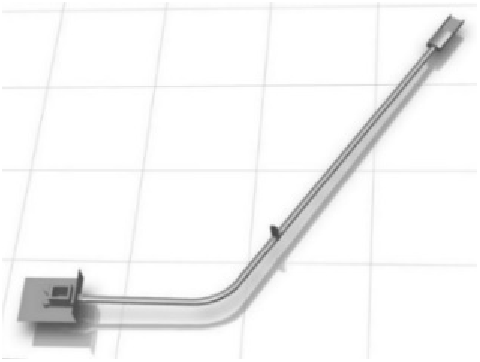


Fig. 2. Calculation area diagram

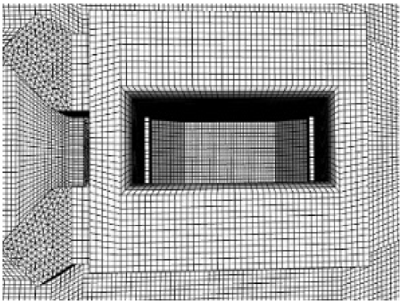


Fig. 3. Grid diagram

The calculation domain is primarily divided using a hexahedral structured grid, with tetrahedral unstructured grids used as secondary grids. In areas such as the inlet and gradient sections, the grid is appropriately refined, while in other parts, the grid density gradually decrease s with increasing distance from the study area. Grid sizes range from 0.1m to 0.3m, with approximately 3.5 million elements. A schematic diagram of the grid division for the double-layer inlet is shown in Figure 3.

3 Research plan and result analysis

3.1 Analytical Plan

For the pore flow pattern, under three different H_H of 2.25,1.85 and 1.64, by setting different horizontal hole heights D_H, change the area ratio of the double-layer inlet λ_A (the cross-section area of the horizontal hole and the shaft A_H / A_v) and analysis the influence of the area ratio of the double-layer inlet λ_A on the discharge characteristics. The specific analysis and research scheme is shown in Table1.

Table 1. Research plan

Scheme number	Horizontal hole size/m		shaft size/m		λ_A
	D_H	B_H	L_v	B_v	
1	4.0	4.0	10.0	8.0	0.2
2	5.0	4.0	10.0	8.0	0.25
3	6.0	4.0	10.0	8.0	0.3

3.2 Effect of Area Ratio on Discharge Capacity

Analyses of water flow.

The total flow rates of the horizontal tunnel, shaft and double-layer intake are defined as Q_H, Q_V and Q_S, respectively. The water depth above the W-W section of the shaft mouth is defined as H_v. Different H_H are set and calculated under different research schemes. In order to explore the influence of area ratio λ_A on the discharge flow, the relative flow Q_r is used to characterize the flow relationship between the horizontal hole and the shaft, and the relative total flow Q'_r is used to characterize the relationship between the total flow under the same h_r, and the data are carried out. Definition:

Relative flow rate of horizontal hole and shaft:

$$Q_r = \frac{Q_H}{Q_v} \tag{1}$$

Relative total flow:

$$Q'_{ri} = \frac{Q_{si}}{Q_{si-1}} \quad i=,2,3 \tag{2}$$

The relative water depth of horizontal tunnel and shaft:

$$h_r = \frac{H_H}{H_v} \tag{3}$$

The calculated data are shown in Table2. Under three relative water depths, the total inflow of the double-layer inlet basically does not change with the increase of λ_A. It shows that in the state of orifice flow, the double-layer discharge is controlled by the section of the spillway tunnel downstream of the inlet and has little to do with the area ratio.

At the same h_r, Q_r increases linearly with λ_A. It shows that the size of the horizontal hole has little effect on the flow distribution of the double-layer inlet. However, when the double-layer inlet is in the hole flow state, it is mainly dominated by the discharge of the shaft.

At different h_r, the size of Q_r is the same under the same λ_A, indicating that Q_r is controlled by the size of the tunnel body under the flow pattern of the hole flow and has little to do with the relative water depth. Therefore, in the design of the diversion tunnel of the double-layer inlet, the size of the horizontal tunnel and the shaft can be designed according to the flow distribution needs during the construction period.

Table 2. Inlet flow under different λ_A

h_r	λ_A	Q'_r	Q_r
2.25	0.2	——	0.11
	0.25	1	0.13
	0.3	1	0.15
1.85	0.2	——	0.11
	0.25	1	0.13
	0.3	1	0.15
1.64	0.2	——	0.11
	0.25	1	0.13
	0.3	1	0.15

Analyses of the Froude number of the water flow.

For the double-layer inlet, select the S-S section of the horizontal hole inlet; analyze the flow F_r of the W-W section at the mouth of the shaft, and calculate the flow F_r of the section by formula (4) and formula (5) respectively:

Froude number of water flow at the entrance of horizontal tunnel:

$$\mathrm{F_{rH}}=\frac{\mathrm{v_H}}{\sqrt{\mathrm{gH_H}}} \tag{4}$$

Froude number of the shaft inlet:

$$F_{rv}=\frac{v_v}{\sqrt{gH_v}} \tag{5}$$

In the formula: v_H is the average velocity of S-S section (m/s); v_v is the average velocity of W-W section (m/s); H_H is the water depth in front of the horizontal hole (m); H_V is the water depth (m) above the W-W section of the shaft mouth. The relationship between different λ_A and the flow F_r of the inlet section is shown in Figure4.

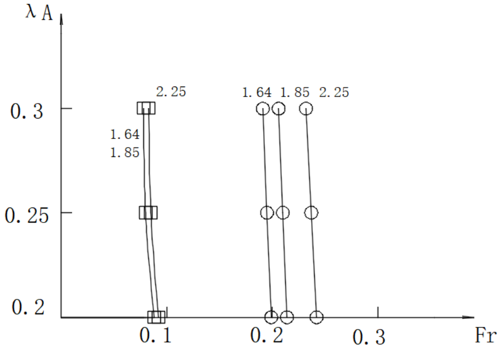


Fig. 4. The relationship curve of F_r and λ_A under different h_r

Under the three relative water depths, F_{rH} and F_{rv} show a decreasing trend with the increase of A, and the decrease of F_{rH} decreases. F_{rv} decreased linearly. F_{rH} basically does not change after the relative water depth decreases to a certain value. F_{rv} decreases with the decrease of relative water depth. It shows that in the hole flow state, it is mainly discharged by the shaft, and the blocking effect of the shaft flow on the horizontal tunnel is greater than that of the horizontal tunnel flow on the shaft discharge. It can be seen that the change of the size of the horizontal hole has no effect on the velocity distribution, and there is no essential difference in the magnitude.

Analyses of the pressure intensity.

The pressure of the double-layer inlet is analyzed by selecting the V-V control section, and the relative pressure is defined:

$$P_r = \frac{P}{H_H} \tag{6}$$

In the formula: P is the average pressure (m) of the V-V cross section.

The relative pressure of the V-V section is calculated for different relative water depths and area ratios. The data are shown in Table3. The results show that under the same hr, the relative pressure remains unchanged regardless of the area ratio. With the increase of h_r, P_r changes linearly. It shows that in the flow pattern of the orifice, the discharge of the double-layer inlet is controlled by the section of the downstream spillway tunnel, which has nothing to do with the size of the inlet.

Table 3. Pressure intensity at V-V section under different λ_A

h_r	λ_A	P_r
2.25	0.2	0.39
	0.25	0.39
	0.3	0.39
1.85	0.2	0.42
	0.25	0.42
	0.3	0.42

1.64	0.2	0.46
	0.25	0.46
	0.3	0.46

Analyses of head loss and its coefficient.

The V-V section is selected as the head loss analysis section of the double-layer inlet section. The calculation method of the head loss coefficient ζ of the inlet section is shown in Formula (7). Under different h_r, the relationship between head loss coefficient and λ_A is shown in figure5.

$$\zeta = h_f / \left(\frac{v_V^2}{2g}\right) \tag{7}$$

Combined with the diagram, it is found that under the three water depth ratios, with the increase of λ_A, the head coefficient ζ increases and the increase amplitude decreases; it shows that when the water depth is high, although the flow rate of the horizontal tunnel accounts for a small share, with the increase of λ_A, the flow rate also increases accordingly, thus increasing the blocking effect on the shaft flow.

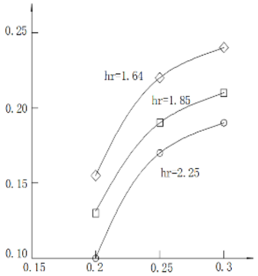


Fig. 5. Curve diagram of relationship between λ_A and ζ

4 Conclusions

(1) Under three different h_r conditions, as the parameter λ_A increases, the total inflow of the double-layer inlet remains relatively unchanged, while Q_r shows a linear increase; both F_{rH} and F_{rv} exhibit a decreasing trend, with F_{rH} decreasing at a reduced rate and F_{rv} showing a linear decrease; the relative pressure P_r remains unchanged; the head loss coefficient ζ exhibits a increasing trend, with it increasing at a reduced rate.

(2) Changes in the area ratio A have a minimal impact on the flow distribution in the double-layer inlet and have virtually no effect on the velocity distribution. During discharge from the double-layer inlet, the flow is primarily controlled by the discharge from the vertical shaft and is influenced by the downstream flood discharge tunnel section.

(3) The hydraulic characteristics of double-layer inlet structures in the flow regime of a submerged flow were analyzed in detail by changing the ratio of the entrance area between the horizontal orifice and the vertical well. This analysis provides valuable

insights for such configurations. In the future, this will plan to investigate the differences in hydraulic characteristics between double-layer inlet structures and single-layer horizontal orifice inlets as well as conventional bell-mouth inlets, aiming to further identify the advantages of double-layer inlets.

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