Experimental study on energy dissipation of annular overflow shaft

GU Jinde, Li Yuan, Zhao Jianjun
Nanjing hydraulic research institute, Nanjing 210029
Corresponding author’s e-mail: Jdgu@nhri.cn

Abstract: The annular shaft, which is widely used in tailings and some large and medium water conservancy project, has the characteristics of simple structure and strong discharge capacity. With the increase of working head, the energy dissipation problem of shaft is becoming much important. Model test results shows that the peak of the hydrodynamic pressure at the bottom of the shaft happens when the water jet merge together, for the water depth $H$ in the shaft is low then, the pre-excavated hydrostatic depth is the main factor of energy dissipation. The fitting formula of the maximum impact pressure is obtained and it is suggested that the energy dissipation depth $h$ should be $0.8D$.

1. Introduction

With the characteristics of simple structure, strong cavitation resistance and large discharge ability, annular shaft is a common drainage facility in tailings pond and fly ash pond. In recent years, vertical shaft drainage was always adopt by some large and medium-sized water conservancy projects [1-4]. With the development of high dam engineering technology, the overflow head of vertical shaft has reached more than 100m. At the same time, due to the direct drop of water flow, energy dissipation of high speed flow is more serious.

The most common energy dissipation method of annular shaft is to make pre-excavate depth in the bottom of the drainage tunnel to form a water cushion energy dissipation area, so that the energy of falling water tongue can be buffered and the direct impact pressure on the bottom can be reduced, which can ensure the stability of the shaft structure. The reasonable energy dissipation depth should not only ensure the safety of shaft structure, but also take economy into consideration. The energy dissipation depth can be determined in many ways. For example, some engineers suggest it to be determined by conjugdined depth of intake flow, and some suggest it to be determined by energy dissipation rate per unit water body [5-6]. Nevertheless, model study, by which dynamic pressure can be get, is thought to be the most effective way. Many scholars [7][8] have put forward Suggestions on energy dissipation depth based on model test results and different conclusions have been drawn due to different test conditions. Therefore, the problem of energy dissipation depth in circular shaft still needs to be further discussed.

Dynamic water impact pressure at the bottom of a shaft is the most direct indicator of energy dissipation effect, and the energy dissipation depth should be determined by combining dynamic water pressure with the impact resistance of the shaft floor. Therefore, the calculation method of fall-flow water pressure is the key to determine the energy dissipation depth. Based on the research background of a high tailings pond drainage shaft, dynamic pressure at the bottom of the shaft under different energy dissipation depth is analyzed, the empirical formula impact pressure is summarized based on
the test data, and energy dissipation water depth in the high drainage shaft is discussed, which provides a basis for related projects.

2. Model construction
The model is built according to a drainage system of overflow tower-drainage tunnel of a tailings pond project. The diameter of the drainage shaft was 5.5m, and the bottom of the shaft was connected to the drainage tunnel. The section of the drainage tunnel was 3.3m×3.3m, which is straight wall semicircular arch. The model is designed according to the gravity similarity criterion by scale of 1:25. The shaft and the drainage tunnel are all made of plexiglass, which not only satisfy the similar roughness, but also easy for observation of the flow pattern. The overflow area at the top of the shaft is enclosed in the steel water tank, while the shaft and downstream drainage tunnel are outside, enhanced by steel structure. Pressure sensors are placed at different place of the shaft, the DASP system of Oriental noise research institute is used for pressure collection and processing. The model test system is shown in Figure 1.

When the drainage system is running, the water level in the shaft rises with the increase of discharge. In this paper, the height from the bottom of the drainage tunnel to the water surface in the shaft is denoted as H, which depends on the discharge ability of the drainage tunnel. The distance from the bottom of the shaft to the bottom of the drainage tunnel is the initial energy dissipation depth, which is denoted as h. The shaft diameter is D. During the test, it can be observed that, with the increase of the discharge flow of the overflow weir, the wall sticking flow, concentrated flow and collision merge flow occur successively in the shaft. In order to compare the variation of the pressure at the bottom of the shaft with different energy dissipation water depths, different initial energy dissipation depth schemes with h= 0.2D, h= 0.5D and h=1D is designed, and the dynamic pressure is tested.

3. Typical flow pattern in shaft
It can be observed that there are two kinds of falling flow patterns in the shaft during the experiment: 1. Uncollision flow, when discharge is very small, falling jet almost no contact with each other, drop points are near the central of shaft, boundary of flow is rather clear, this flow pattern is defined as flow pattern I, as shown in Figure 2(a). 2. Collision flow. With the increase of discharge, the falling jet becomes thicker and the throw distance increases. The flow of different directions crash in the air, The collision effect of jet is more obvious while discharge increase. The air jet collides, merges and disperses, flow boundary blurs under intensive aeration during the drop, the water roll shaft, this flow pattern is defined as flow pattern II, as shown in Figure 2(b).
4. Hydraulic characteristics of energy dissipation zone at shaft bottom

Pressure sensors were installed at different elevations, both in the centre of shaft floor and the side wall, to measure the pressure under different flow rates. Test results are shown in Figure 3. As can be seen, the average pressure in the bottom increases rapidly with the increase of the flow rate under low discharge rate, pressure reach to the peak at flow rate of 15m³/s. Then it gradually decreases with the increase of the flow and reaches to the valley when the flow is about 40m³/s, then the average pressure gradually rises again with the increase of discharge. As can be seen from the perspective of pressure growth trend, when the flow rate exceeds 60m³/s, the pressure growth trend at all measurement points is basically the same. The pressure difference between different measuring points is equivalent to the hydrostatic pressure corresponding to the elevation difference. Peak pressure forms due to insufficient water cushion, and it decreases while the water depth increase. Shaft peak during low flow is insufficient, because the shaft in the inland waters cushion depth drainage of water impact plate, with the increase of discharge shaft after the internal pad increase, direct impact pressure eliminations in the water cushion while discharge is higher than 60m³/s.

The shaft discharge is dimensionless by shaft diameter D, denoted as dimensionless discharge

\[ Q^* = \frac{Q}{\sqrt{gD^5}} \]

The impact pressure at the bottom is defined as the difference between the maximum time-averaged pressure and the hydrostatic pressure, the expression is

\[ \Delta P_{max} = P_{max} - (H + h) \]

in which \((H + h)\) is the actual energy dissipation water depth inside the shaft. The impact pressure under each flow rate is shown in Figure 4. As can be seen from the Figure, the impact pressure increases rapidly with the increase of the flow. It peaks around the dimensionless discharge of 0.06~0.07, and then decreases rapidly with the increase of the discharge. When the flow increases above 0.3, the impact pressure is very small.

Flow pattern in the shaft is observed during the model test, when the dimensionless flow rate is less than 0.02, overflow concentration increased gradually to the shaft center, the drainage tunnel inlet are in a state of free flow (flow I); When the dimensionless flow rate is higher than 0.02, the flow collision...
in the air, water tongue collision point rise gradually with further increases in discharge, water level in shaft rise at the same time (flow II).

5. Discussion on initial energy dissipation depth at shaft bottom
The cause of impact pressure is that the high velocity head acts directly on the bottom, and the velocity head is converted into kinetic energy, that is \( \Delta P = \frac{v_m^2}{2g} \), in which \( v_m \) is the bottom velocity of discharge flow. The initial flow velocity drop into the water surface of the shaft is denoted as \( v' \), it can be inferred that \( \frac{v_m}{v_0} = k \left( \frac{x}{d_0} \right)^n \)

According to the diffusion law of free jet in water cushion. Where, \( k \) and \( n \) are constants, \( d_0 \) is the thickness of the flow, and can be evaluated by \( d_0 = q/v_0 \), where \( q \) is the flow rate of single width. Take the common logarithm of both sides of the formula:

\[
\lg \left( \frac{v_m}{v_0} \right) = \lg k + n \lg \left( \frac{x}{d_0} \right)
\]

It can be obtained that \( k = 1.79, \ n = 0.7663 \) by binary linear regression analysis of model test data, than the formula is \( \frac{v_m}{v_0} = 1.79 \left( \frac{x}{d_0} \right)^{-0.7663} \), as shown in Figure 5, which can be used for dynamic pressure evaluation in approximate engineering.

![Figure 5 bottom velocity fitting curve](image1)

From the test results, peak dynamic load is found in the region between the flow pattern I and flow pattern II, where dimensionless flow rate is about 0.06. Dynamic water impact pressure at the bottom of the shaft under different initial dissipation depth can be calculated according to the formula, and the calculated results are shown in Figure 6. As can be seen, when the initial energy dissipation depth \( h \) increases from 0 to 0.8d, the impact pressure decreases rapidly. When \( h > 0.8d \), the dynamic water impact pressure decreases slowly while it is already very small, and the change trend tends become flat. According to references [5][6], initial energy dissipation depth are suggested to be \( \Delta P / \gamma h = 1 \), the corresponding \( h/D \) is about 0.8 in Figure 6. It is shown that 0.8D is an appropriate initial energy dissipation depth of this project according to the calculation results.

6. Conclusions
The following conclusions can be drawn from the 1:25 hydraulic model test of a discharge shaft: 1. The dynamic pressure at the bottom of the shaft increases first and then decreases with the increase of the discharge. When the annular falling flow begins to merge together, the dynamic water load at the bottom of the shaft come to a peak value. Then, under the influence of the rapidly increasing water depth, the dynamic water load gradually decreases. 2. Initial energy dissipation depth has a direct effect on the peak pressure, the empirical formula, which is fitted with the test data, can be used to obtain the
impact pressure at the bottom of the shaft under different initial energy dissipation depths. From the calculation results, initial energy dissipation water depth of is 0.8D more appropriate for this project.

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