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Hydraulic characteristics of orifice plate

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In some hydropower projects, the height of the dams exceed the level of 300 m. Orifice plate energy dissipater, as a kind of effective energy dissipater with characteristics of economic value, has been welcomed more and more by hydraulics researchers. The energy loss coefficient relating directly to the energy dissipation ratio is an important index for this energy dissipater design. In the present paper, this coefficient and relative parameters, such as contraction ratio of the orifice plate diameter and the flood discharge tunnel diameter, ratio of the orifice plate thickness to the tunnel diameter, and Reynolds number of the flow through orifice, were analyzed by theoretical considerations and their relationship expressions obtained by experiment. It could be concluded that the energy loss coefficient was mainly dominated by the contraction ratio of the orifice plate. The less the contraction ratio of the orifice plate is the larger is this coefficient. The research results demonstrate that the effects of Reynolds number could be neglected on this coefficient when Reynolds number is larger than 10^5 and that the orifice plate's thickness has slight impact on the energy loss coefficient.

[Keywords: Backflow region; Contraction ratio; Energy dissipater; Energy loss coefficient; Orifice plate; Thickness]

Introduction

In some hydropower projects, the height of the dams exceed the level of 300 m, such as 305 m and 315 m for the Jinping first-cascade hydropower project and the Shuangjiangkou hydropower project in Sichuan province, respectively. Over 30 hydropower projects with the height of above 100 m have been completed or are under construction since 2000 in China[1]. For a high dam project, the energy dissipation for flood discharges is an important problem that affects the safety of this project directly. The orifice plate as well as the plug, as a kind of energy dissipaters with sudden reduction and sudden enlargement forms, have been used in the hydropower projects due to their simple structure, convenient construction and high energy dissipation ratio[2,3]. As early as 1960s in the last century, a plug dissipater, similar to orifice plate in energy dissipation mechanism, with the energy dissipation ratio of over 50%, was used in the flood discharge tunnel of the Mica dam in Canada[3]. In 2000, a three-stage orifice plate was applied in the Xiaolangdi projects in china, gets the energy dissipation ratio of about 44% and effectively controls the flow velocity through the gate less than 35 m/s under the condition of the head of 145 m[4,5]. The practical application has proved that it is entirely feasible to utilize orifice plate to dissipate flow's tremendous energy in hydropower project. So it is important to carry out research on related hydraulics problems of orifice plate.

The flow through an orifice plate is shown in Figure 1. There exist the vortex regions of ring form before and after the orifice plate due to sudden reduction and sudden enlargement of the orifice plate, and those vortices are the original regions of energy dissipation. Also, there are strong flow's shear and turbulence layers, where there exists energy loss, in the vicinity of flow's contraction section. There are many studies on the energy dissipaters with sudden reduction and sudden enlargement forms[6,7] focused on orifice plate's incipient cavitations number, embodying its cavitations risk, and its energy loss coefficient, relating to its energy loss ratio. The incipient cavitations number and the energy loss coefficient are closely related with orifice plate's

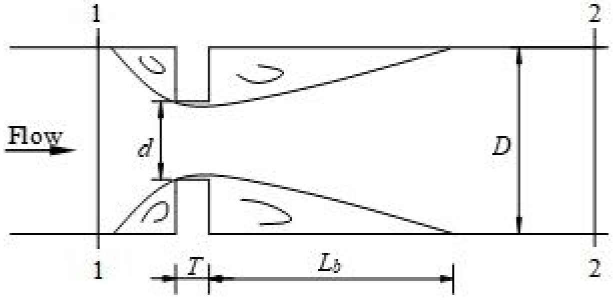

Fig. 1 — Flow through orifice plate

contraction ratio (β), defined as the ratio of the orifice diameter (d) of the energy dissipater and the diameter (D) of flood discharge tunnel, and orifice plate's geometry. With respect to the effects of the contraction ratio of the orifice plate on the incipient cavitations number, Wanzheng[8] regarded that the incipient cavitations number of the orifice plate decreased with the increase of the contraction ratio. The orifice plate's other geometric parameters also have slight impact on its incipient cavitations number. Jianhua[4] deemed that sloping-approach orifice plate is effective to improve the orifice plate cavitations performance, as compared with the sharp-edged and square-edged orifice plates. However, sloping-approach orifice plate is inferior to the other two in energy dissipation ratio.

As stated above, the researches conducted in the past focused mainly on the trend relationship between contraction ratio and energy loss coefficient or incipient cavitations number[9,11]. As a matter of fact, the effect of energy dissipater's thickness, which is closely related with the partition between orifice plate and plug, on energy dissipater's energy loss coefficient, is also remarkable[12,13]. The purpose of the present work, therefore, is to investigate the effects of the geometric parameters, i.e., the contraction ratio and the orifice plate thickness, the hydraulic parameters, i.e., Reynolds number on the energy loss coefficient; and to present an empirical expression of the energy loss coefficient to relating parameters, by means of physical model experiments.

Theoretical Considerations

Definition of head loss coefficient

The flow through the orifice plate energy dissipater for a flood discharge tunnel is shown in Figure 1, in which section 1-1 is located in the positions of 0.5 D before the orifice plate and section 2-2 3.0 D after the orifice plate. The energy equation of the flow between section 1-1 and section 2-2 can be given:

$$z_1 + \frac{p_1}{\gamma} + \frac{\alpha_1 u_1^2}{2g} = z_2 + \frac{p_2}{\gamma} + \frac{\alpha_2 u_2^2}{2g} + \left(\xi_f + \xi_l\right)\frac{u_1^2}{2g} \quad \text{... (1)}$$

where z_1 and z_2 are the elevation heads at sections 1-1 and 2-2, respectively; p_1 and p_2 are the average pressures at sections 1-1 and 2-2, respectively; u_1 and u_2 are the average velocities at sections 1-1 and 2-2, respectively; α_1 and α_2 are the kinetic energy correction factors at sections 1-1 and 2-2, respectively; γ is the specific weight of water; g is the acceleration of gravity; and ξ_f and ξ_l are the frictional head loss and local head loss coefficients, respectively. For the tunnel with the bottom slope of zero, $z_1 = z_2$. When the tunnel has same diameter D, $u_1 = u_2 = u$ is the average velocity of the tunnel based on continuity equation. Let $\alpha_1 = \alpha_2 = 1.0$, neglect the effects of the frictional head loss, i.e., $\xi_f = 0$, and let $\xi_l = \xi$, and then Eq. (1) becomes:

$$\xi = \frac{p_1 - p_2}{0.5\rho u^2} = \frac{\Delta p}{0.5\rho u^2} \quad \text{... (2)}$$

This is the energy loss coefficient of the orifice plate energy dissipater, where $\triangle p = p_1 - p_2$, is the pressure difference between sections 1-1 and 2-2 and ρ is the density of water.

Dimensional analysis

There are many parameters which affect the energy loss coefficient of orifice plate, and the relevant parameters of dimensional analysis may include the density of water ρ (kg/m^3), the dynamic viscosity of water μ (N.s/m^2), the tunnel diameter D (m), the orifice plate diameter d; the orifice plate thickness T (m); the average flow velocity in tunnel u (m/s), the difference between p_1 and p_2, $\triangle p$ (Pa). Because each of the above parameters is a function of the initial independent parameters, an expression about the above parameters can be obtained:

$$\Delta p = f\left(D, d, T, \rho, \mu, u\right) \quad \text{... (3)}$$

This relationship could be rewritten in terms of dimensionless parameters:

$$\Delta p / \left(0.5\rho u^2\right) = f\left(d/D, T/D, uD\rho/\mu\right) \quad \text{... (4)}$$

That is:

$$\xi = f\left(\beta, a, R_e\right) \quad \text{... (5)}$$

Where Re is Reynolds number, $a=T/D$, $\beta=d/D$. Eq. (5) indicates that the energy loss coefficient, ξ is the function of β, α and Re. The study procedure was outlined considering variable parameters in the energy loss coefficient variations in Eq. (5) to find out the effects of each parameter independently on it.

Model Experiment

Model arrangement

The physical model experimental set-up consists of an intake system, a tank, a flood discharge tunnel with an orifice plate energy dissipater, and a return system with a rectangular weir (Fig. 2). The diameter (D) of the tunnel model is 0.21 m and the length of the tunnel model is 4.75 m, i.e., 22.6 D from the intake to

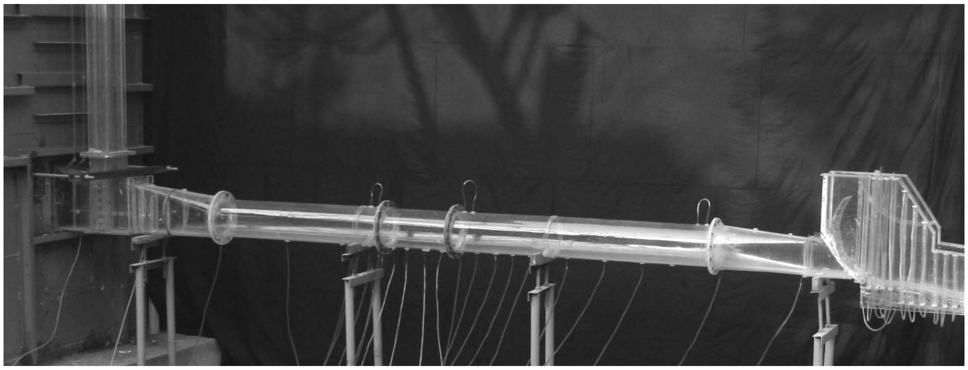

Fig. 2 — Discharge tunnel model

Table 1 — The geometry of every model

Model No.	D(m)	d(m)	T(m)	β	α
M_1	0.21	0.084	0.0210	0.4	0.10
M_2	0.21	0.105	0.0210	0.5	0.10
M_3	0.21	0.126	0.0210	0.6	0.10
M_4	0.21	0.147	0.0210	0.7	0.10
M_5	0.21	0.168	0.0210	0.8	0.10
M_6	0.21	0.147	0.0105	0.7	0.05
M_7	0.21	0.147	0.0315	0.7	0.15
M_8	0.21	0.147	0.0420	0.7	0.20
M_9	0.21	0.147	0.0525	0.7	0.25

the pressure tunnel outlet at the gate. The orifice plate energy dissipater was placed at the positions of 10.0 *D* from the tunnel intake and of 12.6 *D* to the outlet at the gate. The water head about 10.0 *D* could be presented by the intake system and the tank. The opening of the gate could be changed conveniently. Thirty-five pieces of small plastic tube installed along tunnel wall were utilized to measure wall pressure. Due to flows change violently in the vicinity of orifice plate, the distance of two plastic tubes is 0.25D from 0.5*D* place before orifice plate to 4.0*D* place after orifice plate. The geometry of every orifice plate and the geometry of flood discharge tunnel are shown in Table 1 and Figure 3.

Experiment phases

The experiment phases are designed according to Eq. (5). There are two phases in the experiment Phase No. 1 measuring the wall pressures before 0.5D orifice plate and after 3.0D orifice plate and tunnel's average velocity when α is 0.10 and β is 0.40, 0.50, 0.60 and 0.70. The purpose of the Phase No. 1 experiment was to investigate the relationship between the energy loss coefficient ξ and contraction ratio β when α is constantly. The measurement method of Phase No. 2 is similar to that of Phase No.1, but contraction ratio β is constantly 0.7 and α is 0.10, 0.15, 0.20 and 0.25. The purpose of the Phase No. 2 experiment was to investigate the relationship between the energy loss coefficient ξ and dimensionless thickness α, when β is constant. The energy loss coefficient is calculated on the basis of Eq. (2).

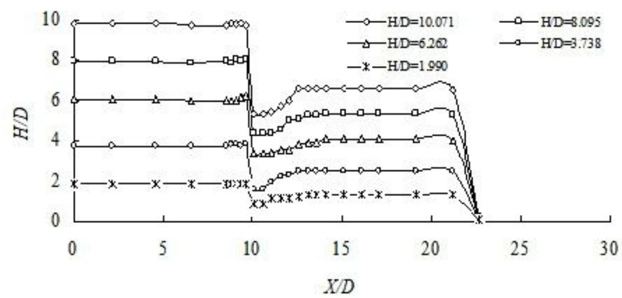

Fig. 3 — Pressure distributions along the tunnel (β = 0.50, α = 0.10)

Experiment data

The results of Phase No. 1 and Phase No. 2 are shown in Table 1 and Table 2, respectively. The meanings of every symbol in Table 1 and Table 2 are: p_1 (Pa) is the wall pressure before 0.5*D* orifice plate; p_2 (Pa) is the wall pressure after 3.0*D* orifice plate; *Re* is Reynolds number; *H* (m) is the height of tank water (water level); *Q* (m^3/s) is discharge volume; and *n* is opening level of control gate.

Discussion

Figure 3 is about the pressure distributions along the tunnel wall when β is 0.50 and α is 0.10 indicates that flow may recover normally after 3.0*D* orifice plate, and flow starts to change dramatically in the vicinity of 0.5*D* before orifice plate. So it is reasonable to select p_1 before 0.5*D* orifice plate and p_2 after 3.0*D* orifice plate to calculate the head loss coefficient ξ.

Table 2 — Data of phase No.1 (a=0.1, n=0.25)

β	H(m)	Q(m^3/s)	Re($\times 10^5$)	$p_1/\rho g$ (m)	$p_2/\rho g$ (m)	ξ	Average ξ
0.4	2.08	0.017208	0.091484	2.065	0.839	95.36	94.69
	1.69	0.015662	0.083267	1.673	0.686	94.61	
	1.27	0.013789	0.073311	1.269	0.513	93.49	
	0.82	0.010595	0.05633	0.795	0.340	95.30	
0.5	2.12	0.02176	0.115688	2.040	1.385	32.56	31.52
	1.70	0.02082	0.110689	1.690	1.100	32.00	
	1.32	0.018088	0.096164	1.253	0.823	30.90	
	0.79	0.014005	0.074459	0.785	0.528	30.81	
	0.42	0.009487	0.050437	0.400	0.280	31.35	
0.6	2.10	0.026338	0.140024	2.048	1.720	12.20	12.00
	1.72	0.024076	0.128	1.691	1.402	11.72	
	1.34	0.021132	0.112347	1.305	1.087	11.48	
	0.82	0.015944	0.084768	0.791	0.665	11.65	
	0.38	0.010253	0.054513	0.366	0.308	12.97	
0.7	2.10	0.028115	0.149474	2.056	1.912	4.33	4.25
	1.69	0.025331	0.134672	1.660	1.542	4.32	
	1.28	0.021887	0.116361	1.253	1.165	4.32	
	0.81	0.017441	0.092724	0.782	0.727	4.25	
	0.39	0.01299	0.069061	0.389	0.360	4.04	
0.8	2.10	0.030146	0.160269	2.043	1.987	1.45	1.41
	1.70	0.027358	0.145449	1.653	1.607	1.45	
	1.28	0.023815	0.12661	1.242	1.206	1.49	
	0.79	0.018863	0.100287	0.765	0.745	1.32	
	0.41	0.013789	0.073311	0.397	0.386	1.36	

Figure 4 is about the curves which embody the relationships between water level H and the energy loss coefficient ξ when β is 0.70 and α is 0.10. It demonstrates that the energy loss coefficient ξ increases with the increase of water level H at low water level, but when water level H is more than 8.9 m (Reynolds number Re is approximately 0.7×10^5 at this time), water level H has little impact on the energy loss coefficient ξ. The relationship between water level H and the energy loss coefficient ξ imply indirectly that when Reynolds number Re is less than 10^5, the energy loss coefficient ξ increases with the increase of Reynolds number Re, but when Reynolds number Re is more than 10^5, the energy loss coefficient ξ hardly varies even if Reynolds number Re varies.

Figure 5 is drawn by using the data when H is 2.1 m in Table 2, which demonstrates that when dimensionless thickness a is constant, the energy loss coefficient ξ decrease with the increases of contraction ratio β. Figure 6 is about the relationship between the energy loss coefficient ξ and the

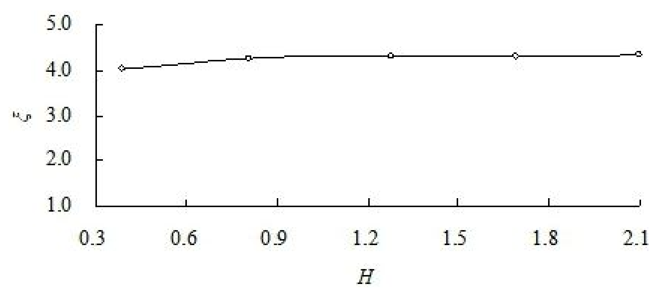

Fig. 4 — The relationship between H and ξ

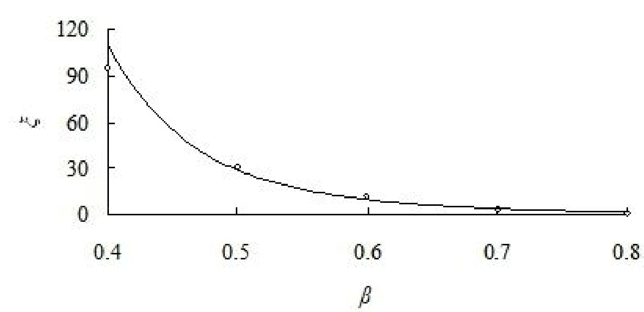

Fig. 5 — The relationship between ξ and β (a=0.1

Table 3 — Data of phase No.2 (β=0.7, n=0.75)

A	H (m)	Q(m^3/s)	Re(×10^5)	$p_1/\rho g$ (m)	$p_2/\rho g$ (m)	ξ	Average ξ
	2.12	0.066278	0.352365	1.900	1.111	4.40	
	1.70	0.059809	0.317973	1.530	0.909	4.08	
0.05	1.30	0.050995	0.271115	1.150	0.695	4.11	4.29
	0.78	0.038757	0.206051	0.710	0.437	4.27	
	0.41	0.026744	0.142185	0.380	0.240	4.60	
	2.11	0.067411	0.35839	1.870	1.150	3.73	
	1.70	0.060627	0.322322	1.510	0.940	3.65	
0.15	1.29	0.052285	0.27797	1.140	0.709	3.71	3.70
	0.80	0.040555	0.215608	0.715	0.460	3.65	
	0.40	0.027358	0.145449	0.370	0.250	3.77	
	2.09	0.067885	0.360911	1.855	1.182	3.43	
	1.72	0.061816	0.328642	1.515	0.990	3.23	
0.20	1.32	0.052977	0.281652	1.150	0.742	3.42	3.38
	0.81	0.040397	0.214771	0.700	0.471	3.30	
	0.41	0.027633	0.146908	0.370	0.255	3.54	
	2.11	0.069028	0.366989	1.860	1.245	3.03	
	1.69	0.061907	0.32913	1.490	1.000	3.01	
0.25	1.30	0.053151	0.282575	1.140	0.763	3.14	3.04
	0.82	0.041743	0.221924	0.720	0.495	3.04	
	0.41	0.027977	0.148739	0.365	0.265	3.00	

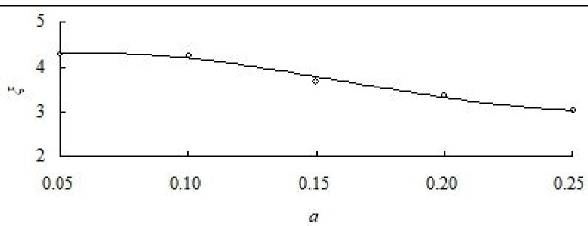

Fig. 6 — The relationship between ξ and a (β=0.7)

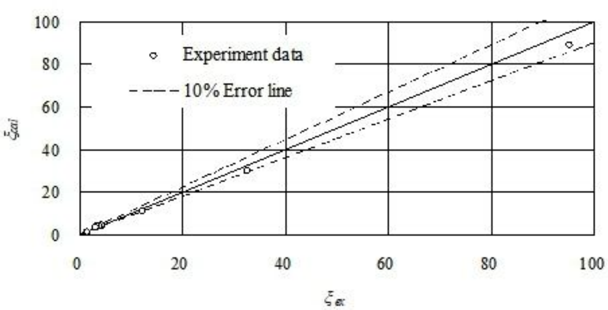

Fig. 7 —The error of calculated data

dimensionless thickness a according to the data when H is 2.1 m in Table 3. Figure 6 shows that when the contraction ratio β is constant, the energy loss coefficient ξ also decreases with the increase of the dimensionless thickness a. The empirical expression, by means of the experiment results when H is 2.1 m in Table 2 and 3, could be obtained:

$$\xi = \left(35.43\times a^3 - 17.09a^2 + 1.71a + 0.41\right)\beta^{-5.98} \quad ...\ (6)$$

This expression is valid for β = 0.4 – 0.8, α = 0.05 – 0.25 and $Re > 0.7\times10^5$.

Let the relative error E_r between the calculated ξ_{cal} by using Eq. (6) and the experiment ξ_{ex} of the energy loss coefficients as:

$$E_r = \frac{\left|\xi_{cal} - \xi_{ex}\right|}{\xi_{cal}}\times100\% \quad ...\ (7)$$

The results of the error analysis are shown in Figure 7. Which indicates that the maximum error of Eq. (6) is less than 10%.

Conclusion

For an orifice plate energy dissipater, its energy loss coefficient ξ is the function of the contraction ratio of the orifice plate β, the ratio of the orifice plate thickness α and the Reynolds number Re of the flow. And the effects of Re could be neglected on ξ when this number is larger than 0.7×10^5.

The contraction ratio β is the key factor that dominates the energy loss coefficient ξ. The less is the contraction ratio β, the bigger is the energy loss coefficient ξ. The relationship of ξ, β and α could be expressed as Eq. (6). Comparing with the physical model experimental results from Table 2 and Table 3, the relative errors of Eq. (6) are all less than 10%.

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