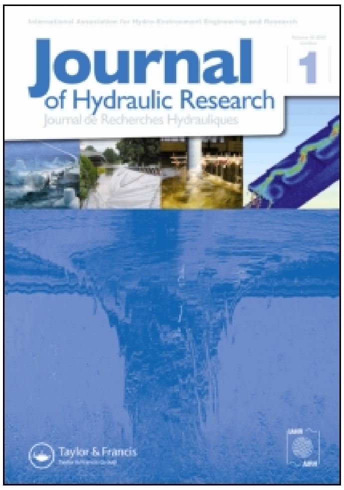

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Head loss coefficient of orifice plate energy dissipator

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Technical note

Head loss coefficient of orifice plate energy dissipator

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ABSTRACT
Orifice plates as an effective energy dissipator have been used in hydropower projects. The head loss coefficient, relating directly to the energy dissipation ratio, is an important index of these elements. This coefficient and parameters such as the contraction ratio of the orifice plate diameter and the flood discharge tunnel diameter, the ratio of the orifice plate thickness to the tunnel diameter, the dimensionless recirculation length and the Reynolds number were theoretically analysed, and relationships were obtained by numerical simulations and physical model experiments. The head loss coefficient is mainly dominated by the contraction ratio and the ratio of the orifice plate thickness by the effects of the recirculation region. The less the contraction ratio of the orifice plate, the larger the recirculation length and height, and the larger the head loss coefficient. An empirical expression allows us to determine the head loss coefficient.

Keywords: Contraction ratio, energy dissipator, head loss coefficient, orifice plate, recirculation

1 Introduction

Energy dissipation is an important issue affecting the safety of high dams. These may currently exceed a height of 300 m, such as the *Jinping* first-cascade hydropower project or the *Shuangjiangkou* hydropower project in the Sichuan Province, China. Over 30 Chinese hydropower projects higher than 100 m have been completed or are under construction since 2000. Their energy dissipation is characterized by a deep valley, high head and large discharge (Lin 1985). The power of the flood discharge, like the *Xiluodu* hydropower project with 100 million kW, is one of the biggest in the world.

The orifice plate and the plug as a kind of energy dissipator involving sudden cross-sectional variations have been used due to their simplicity, convenient construction and high dissipation ratio. The plug energy dissipator, with a dissipation ratio of over 50%, was used for Mica dam, Canada (Russell and Ball 1967, Xiang and Cai 1999), while the orifice plate energy dissipator, used in the *Xiaolangdi* project in China, has a dissipation ratio of about 44% (Wu *et al.* 1995).

The flow through an orifice plate is shown in Fig. 1, involving the vortex regions of ring form up- and downstream of the orifice plate due to sudden cross-sectional changes. These vortices are the origin of energy dissipation. There are several forms of orifice plates, such as the square-edged orifice plate (Cai and Zhang 1994), the sloping-approach orifice plate, the sharp-edged orifice plate (Zhang and Cai 1999), or the orifice plate with ring (Chai *et al.* 1992, Li *et al.* 1997). Research on the orifice plate has particularly been directed to energy dissipation and the cavitation characteristics, which are closely related to the contraction ratio and the orifice plate geometry. Other aspects investigated include cavitation prediction (Ball and Tullis 1975), critical Reynolds number for orifice flows (Lakshmana Rao *et al.* 1977), separated flow (Mehta 1981), asymmetric flow in symmetric expansions (Graber 1982), discharge equation of orifice meters (Prabhata 2006) or vapour

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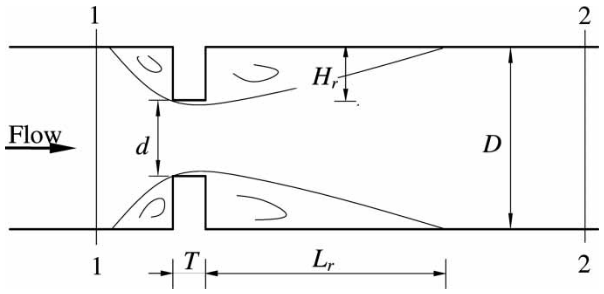

Figure 1 Flow through orifice plate

cavity collapse location from a super-cavitating orifice plate (Smith *et al.* 2008).

With respect to the effects of contraction ratio on energy dissipation, Bullen *et al.* (1987), Wang and Yue (1987) and Fossa and Guglielmini (2002) obtained similar results for flows across either a sudden reduction or a sudden expansion. The energy losses of both flows increased as the contraction ratio reduced. Zhao (1993) stated that the sharp-edged orifice plate has the maximum energy dissipation ratio under otherwise identical contraction ratio among the square-edged, the orifice plate with ring and the sloping-approach flow orifice plate, respectively (Cai and Zhang 1994, Wu *et al.* 1995).

Wang and Yue (1987) presented an approximate method to calculate the loss coefficients of orifice plates by means of physical model experiments. These are $\zeta_1 = (1/C_c - 1)^2$ for sudden contractions and $\zeta_2 = (1/C_c - \beta^2)^2$ for sudden enlargements, respectively, where $C_c = A_c/A_d$ is the area ratio of contracted flow section A_c to orifice section A_d, $\beta = d/D$ is the diameter ratio of orifice d and tunnel D. The loss coefficients are related to A_c and β, but not to the orifice plate thickness T. Cai and Zhang (1994) investigated the effects of orifice plate thickness on the loss coefficients for $\beta = 0.69$ and found that it decreases with an increase in T.

Cavitation performance is another item of the orifice plate characterized by its incipient cavitation number. This is related to the contraction ratio and the form of the orifice plate. Takahashi *et al.* (2001) and Zhang (2003) observed that the incipient cavitation number of an orifice plate decreases as the contraction ratio increases, resulting in a better cavitation performance. Zhang and Cai (1999) stated that the sloping-approach orifice plate improves its cavitation performance when compared with the sharp-edged and square-edged orifice plates. Chai *et al.* (1992) and Li *et al.* (1997) developed the orifice plate with ring, thereby decreasing the incipient cavitation number and eliminating the cavitation risk.

Past research focused mainly on the effects of contraction ratio and orifice plate geometry on either energy dissipation or cavitation performance. However, the effects of other parameters on the orifice plate performance are also important, including hydraulics and geometry. The recirculation length L_r and height H_r of the flow contraction determine the size of the vortex region, i.e. the energy dissipation region beyond the orifice plate. The orifice plate thickness T has an effect on L_r because of the length decrease with an increase in T.

The purposes of this work are to investigate the effects of contraction ratio and the ratio of orifice plate thickness on recirculation length and height. To analyse the latter effects on the head loss coefficient, an empirical expression is provided by means of numerical simulations and physical model experiments.

2 Theoretical considerations

For flow through an orifice plate as shown in Fig. 1, sections 1–1 and 2–2 are located 0.5D upstream and 3.0D downstream of the orifice plate, respectively. For a horizontal set-up, identical diameters D, a kinetic energy correction factor of 1.0 and neglect of fluid friction, the head loss coefficient ξ is, based on the energy and continuity equations,

$$\xi = \frac{p_1 - p_2}{0.5\rho u^2} = \frac{\Delta p}{0.5\rho u^2}, \tag{1}$$

where p_1 and p_2 are the average pressures at sections 1–1 and 2–2, respectively, u the average approach flow velocity and ρ the density of water.

The parameters required to design an orifice plate energy dissipator are Δp and L_r, both of which depend on the basic parameters

$$\Delta p, L_r = \mathrm{f}\big(D, d, T, \rho, \mu, g, u\big), \tag{2}$$

where μ is the dynamic fluid viscosity, and g the acceleration of gravity. Equation (2) may also be expressed as

$$\xi, l_r = \mathrm{f}(\beta, \alpha, \mathsf{R}), \tag{3}$$

where $l_r = L_r/D$, $\alpha = T/D$ and $\mathsf{R} = uD/(\mu/\rho)$ is the approach flow Reynolds number. The governing parameters were varied to determine the head loss coefficient and the dimensionless recirculation length.

3 Methodology

3.1 *Numerical simulations*

A re-normalization group k-ε model was used to calculate the hydraulic flow parameters simulating the flow inside extremely variable boundary forms as well as its high precision and calculation stability (Stamou *et al.* 2008). For steady and incompressible flows, the governing model equations include continuity, momentum and the k–ε closure (Yang and Zhao 1992).

The boundary conditions were treated as follows. At the inflow (subscript *in*) boundary, the turbulent kinetic energy k_{in} and the turbulent dissipation rate ε_{in} were defined, respectively, as

$$k_{in} = 0.0144u_{in}^2, \quad \varepsilon_{in} = \frac{k_{in}^{1.5}}{0.25D}, \tag{4}$$

where u_{in} is the average inflow velocity. At the outflow boundary, the flow was considered fully developed. The wall boundary is controlled by the wall functions (Xia and Ni 2003). A symmetric boundary condition was adopted, i.e. the radial velocity on the symmetry axis is zero.

Three kinds of computational phases were simulated, namely Phase 1 calculating ξ and l_r within a range of $\mathsf{R} = 9.00 \times 10^4$ to 2.76×10^6 for $\beta = 0.50$ and $\alpha = 0.10$, to define the effect of R on ξ (or l_r). Phase 2 aimed to calculate l_r for different β and α if $\mathsf{R} = 1.80 \times 10^5$. Phase 3 allowed to determine ξ for conditions identical to Phase 2 to discuss the variations of ξ with β and α.

The approach flow diameter was $D = 0.21$ m. Numerical simulations ranged from 6D upstream to 8D downstream of the orifice plate. The entire computational domain has $70{,}000 + 5000\ \alpha\beta$ grids considering the symmetry conditions, with (2.1×10^{-3} m) $\times$ (2.1×10^{-3} m) as cell size. ξ was calculated by means of Eq. (1), in which the positions of p_1 and p_2 were placed 0.5D ahead the orifice plate and at 3D beyond it, respectively.

3.2 *Physical model experiments*

The physical model set-up consisted of an intake system, a tank, a flood discharge tunnel with an orifice plate energy dissipator and a return system with a rectangular weir (Fig. 2). The tunnel diameter was 0.21 m and its length 4.75 m, i.e. 22.6D from the intake to the tunnel outlet controlled by a variable gate opening. The orifice plate was placed 10D from the tunnel intake and 12.6D from the outlet. The available water head was 10D. Figure 3 shows the five orifice plates used.

Physical model experiments were conducted at the High-speed Flow Laboratory of Hohai University, Nanjing, China. Experimentation included (1) $\beta = 0.40$, 0.50, 0.60, 0.70 and 0.80 for $\alpha = 0.10$ and (2) $\alpha = 0.05$, 0.10, 0.15, 0.20 and 0.25 for $\beta = 0.70$.

4 Results and discussions

4.1 *Recirculation length*

Table 1 states the numerical results of l_r and R, and of ξ and R for $\beta = 0.50$ and $\alpha = 0.10$. Note that ξ and l_r hardly vary with R for $9.00 \times 10^4 \le \mathsf{R} \le 2.76 \times 10^6$. Therefore, the effect of R on either ξ or l_r is negligible in the considered range, and l_r and ξ depend only on the orifice plate geometry, i.e. β and α. Equation (3) then reads

$$\xi, l_r = \mathrm{f}(\beta, \alpha). \tag{5}$$

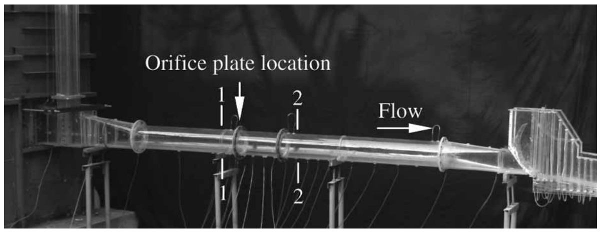

Figure 2 Experimental model

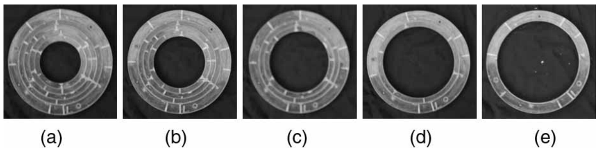

Figure 3 Orifice plate energy dissipator models with $\beta =$ (a) 0.40, (b) 0.50, (c) 0.60, (d) 0.70, (d) 0.80

Figure 4 shows the numerical results of l_r for various β and α if $\mathsf{R} = 1.8 \times 10^5$, in which β varies from 0.40 to 0.80 and α from 0.05 to 0.25. Note that l_r decreases as β increases for any α, i.e. from 3.40 to 1.20 with an increase in β from 0.40 to 0.80 for $\alpha = 0.10$; it also decreases as α increases for any β.

4.2 *Head loss coefficient*

Figure 5 shows the numerical results of ξ for various β and α if $\mathsf{R} = 1.80 \times 10^5$. Note that ξ, like l_r, decreases as β increases for

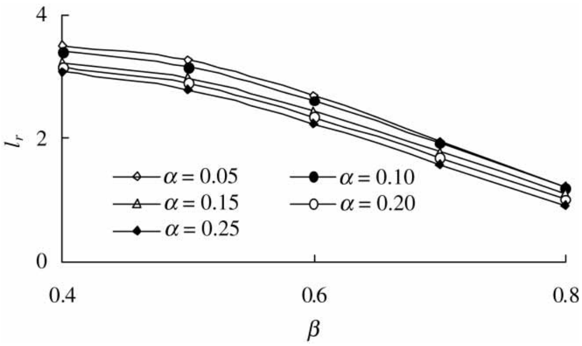

Figure 4 Variation of l_r with β for $\mathsf{R} = 1.8 \times 10^5$

Table 1 Variations of l_r and ξ with R for $\beta = 0.50$, $\alpha = 0.10$

R	9.00×10^4	1.80×10^5	9.20×10^5	1.84×10^6	2.76×10^6
l_b	3.14	3.15	3.15	3.15	3.15
ξ	31.00	31.20	31.20	31.20	31.20

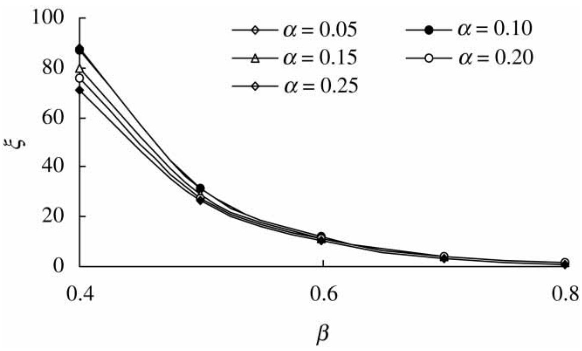

Figure 5 Variations of ξ with β for $\mathsf{R} = 1.8 \times 10^5$

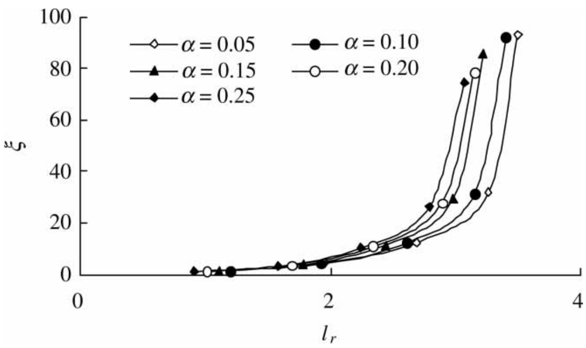

Figure 6 Variations of ξ with l_r

any α and varies from 93.00 to 1.50 as β increases from 0.40 to 0.80 for $\alpha = 0.05$. ξ also decreases with α for any β. Table 2 states the experimental results of ξ for various β and α. These were remarkably close to the numerical simulation results of Fig. 5.

The head loss coefficient ξ expresses the pressure difference ahead and beyond the orifice plate relative to the velocity head based on Eq. (1), stating the amount of energy dissipation mainly due to the recirculation vortex downstream of the orifice plate resulting from intensive shear stresses and friction. The energy dissipation ratio of the orifice plate is therefore closely related to the recirculation characteristics, including l_r and h_r.

Figure 6 shows the effect of l_r on ξ as obtained from Figs 4 and 5. The head loss coefficient ξ is obviously limited to 20 if $l_r < 2.69$ for $\alpha = 0.25$, while it increases rapidly for $l_r > 2.69$ for this α. Note that these results are also related to h_r. The height increases with a decrease in β because $h_r = (1 - \beta)/2$. Since the extent of the vortex region beyond the orifice plate has a cubic relation with the characteristic parameter D, a combination of l_r and h_r significantly changes this water volume. It is concluded that β directly affects its magnitude by the recirculation region, thus governs the head loss coefficient.

ξ is controlled by β, thus essentially by the magnitude of the recirculating water volume. Using the data of Fig. 5, the best fit is

$$\xi = \frac{0.7418}{\alpha^{0.1142}} \times \left(\frac{3.196}{\beta^4} - \frac{5.646}{\beta^2} + 2.45\right) \qquad (6)$$

provided $0.05 \leq \alpha \leq 0.25$, $0.4 \leq \beta \leq 0.8$ and $\mathsf{R} > 10^5$.

Table 2 Variations of ξ with β and α

	α				
β	0.05	0.10	0.15	0.20	0.25
0.40	/	95.30	/	/	/
0.50	/	32.50	/	/	/
0.60	/	12.20	/	/	/
0.70	4.40	4.33	3.73	3.43	3.03
0.80	/	1.45	/	/	/

Let the relative error E_r between calculated (subscript *cal*) ξ_{cal} and numerically (subscript *nu*) simulated head loss coefficients ξ_{nu} be

$$E_r = \frac{|\xi_{cal} - \xi_{nu}|}{\xi_{cal}} \times 100\%. \qquad (7)$$

Data analysis indicates that the maximum error of Eq. (6) is less than $\pm 10\%$ on the basis of the 25 tests. Equation (6) is therefore recommended for design purposes.

5 Conclusions

The head loss coefficient of an orifice plate energy dissipator and the dimensionless length of the recirculation region are functions of the contraction ratio, the ratio of orifice plate thickness and the approach flow Reynolds number. The latter effect was demonstrated to be negligible if $\mathsf{R} > 10^5$. The contraction ratio is the key factor in terms of head losses and recirculation length. The smaller the contraction ratio, the larger is the head loss coefficient. The relationship among these parameters is expressed in Eq. (6). A comparison between the numerical simulation and the physical test results indicates relative errors below $\pm 10\%$.

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Notation

A_c = reduction of flow area by orifice plate
A_d = orifice area
$C_c = A_c/A_d$
D = approach flow diameter
d = orifice plate diameter
H_r = recirculation height
h_r = dimensionless recirculation height
g = acceleration of gravity

k_{in} = turbulence kinetic energy of approach flow
L_r = recirculation length
l_r = L_r/D, dimensionless recirculation length
p_1 = pressure at section 1–1
p_2 = pressure at section 2–2
$\Delta p = p_1 - p_2$, pressure difference
R = Reynolds number of approach flow
T = orifice plate thickness
u = average approach flow velocity
u_{in} = average inflow velocity
α = T/D, ratio of orifice plate thickness to approach flow diameter
β = d/D, contraction ratio of orifice plate diameter and approach flow diameter
μ = dynamic viscosity of water
ρ = density of water
ξ = head loss coefficient

Subscripts

r = recirculation
in = inflow boundary
cal = calculated
ex = experimental
nu = numerical

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