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HYDRAULIC CHARACTERISTICS OF ROTATIONAL FLOW SHAFT SPILLWAY FOR HIGH DAMS

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ABSTRACT

Flood discharge and energy dissipation of large-scale hydraulic and hydroelectric projects are two key technological issues in project planning, design and construction phases. Hydraulic characteristics research of new type high dam flood discharge and energy dissipation facility is one of the major research directions of high-speed hydraulic. To deal with problems of flood discharge and energy dissipation faced in large-scale hydraulic and hydroelectric projects development such as high dam, large discharge and narrow river valley and so on, this paper proposes a new internal rotational flow shaft spillway which suits high arch dam and analyzes the design criteria and size of each part. Discharge volume and ratio of energy dissipation verifications are conducted to the designed internal rotational flow shaft spillway through physical modeling test. Results show that this new discharge and dissipation facility has simple structure; stable discharge volume with good discharge capacity, high ratio of energy dissipation and its project investment is low. Besides, this paper also analyzes the discharge performance of this new discharge and dissipation facility and proposed its discharge function relational expression based on modeling test results. This project research can offer theoretical basis to further body optimization and engineering application of discharge and dissipation facility.

Keywords: rotational flow shaft spillway; discharge volume; ratio of energy dissipation; model.

1. INTRODUCTION

To date, the major areas where China develops hydroelectric energy mainly concentrate in southwest part. Heights of constructed large-scale hydropower projects are mostly higher than 150m. From projects constructed and being constructing, high arch dam has become one of the primary dam types of large-scale hydroelectric projects, for example, dams in Ertan, Xiaowan, Xiluodu, Jinping, Goupitan, Baihetan and Wudongde etc. all adopted high arch dam arrangement form. These projects have features of “narrow river valley, high water head and large discharge volume”. The features bring severe issues of flood discharge and energy dissipation. Therefore, in terms of design of release structure, general layout framework combined by dam body trepanning discharge and shore-side spillway or spillway water diversion is mostly adopted. Due to the narrow canyon riverbed and high discharge volume, the construction of flood releasing structure is very difficult. If shore-side spillway cannot be constructed due to landform limitations of alpine and gorge region, except in dam body surface outlet and middle outlet, shore-side spillway is additionally needed to meet discharge needs. That will increase the cost a lot. Moreover, high-speed water flow will bring special phenomena like mixed gas, pulsation, vibration, cavitations, cavitations erosion and pulverization, harming the security of water releasing structure and downstream river channel environment. Therefore, searching for new type internal discharge and dissipation facility for high dams has been always a research key point at home and abroad. Long before in 1960s, C. Drioli from Italy and D. Jeanpierre from France et al. had begun research of rotational flow shaft spillway and obtained some research results related to energy dissipation which were applied to some degree in former Soviet Union, France, Italy and China. Nowadays, these applied rotational spillways are mostly built in medium-low internal with height less than 100m. Discharge capacity of single outlet is generally smaller than $600m^3/s$, and ratio of energy dissipation less than 60%. Besides, the sizes of producing rotating flow facilities of shaft are relatively larger, so the construction cost is high. And they are not suitable for high arch dam. This research proposed an internal rotational flow shaft spillway which suits high dam. It has simple structure, small size, low building cost, convenient construction and extensive application range. In addition, its discharge volume is large and ratio of energy dissipation is also high. This water discharge and energy dissipation facility is constituted of water inlet section, tangential rotating flow segment, tapered segment, shaft segment, cushion pool segment and water outflow segment. Water flow is formed through water inlet section, and then rotated by rotating parts and tapered segment. The water rotated clings to wall surface in shaft. A stable cavity is formed in the middle. After the energy of water flow being dissipated when water crashes cushion pool in the lower part of shaft, water discharges towards to downstream through horizontal outlet. Hydraulic modeling test verification is conducted to the proposed design scheme, discharge capacity and ratio of energy dissipation of internal rotational shaft spillway is analyzed. Hydraulic characteristics of this scheme are further studied. These all together can offer theoretical basis and technological support to further optimization of this new type water discharge and energy dissipation facility and engineering application.

2. SCHEME DESIGN

The proposed internal rotational flow shaft should combine tightly the actual conditions of China high dam construction. On the basis of features of internal rotational flow shaft, the other following conditions should also be satisfied:

(1) Dam height of high arch dam should be 300m;
(2) Discharge capacity of single spillway reaches 2000～3000m^3/s;
(3) Intake water head is 20～40m;
(4) Ratio of energy dissipation of this discharge and dissipation facility should be bigger than 70%;
(5) Outlet water velocity should be controlled to stay in the water flow speed range that will not cause harmful secondary phenomenon.

2.1 Water intake and inlet

The cross-section of water intake becomes small gradually from big rectangle. Entrance top is oval curve. Its long axis equals with the height of arch door b , short axis is 0.35 b . It is convenient for connection of water intake and non-pressure conduit and transition section. It also lowers Fr (Froude number) and increases amount of cavitations of flow discharge.

The elevation of conduit entrance baseboard and area of radial gate outlet A_0 ($A_0 = a \times b$; a is the width of outlet, b is the height of outlet) are determined by discharge volume Q_0 required. Their relation is as follow:

$$Q_0 = \varphi_0 \xi A_0 \sqrt{2g(H_0 - \xi b)} \tag{1}$$

Where, φ_0 is velocity coefficient of intake; ξ is shrinkage coefficient behind the floodgate when water is discharged through the radial gate, according to existing test results, shrinkage coefficient ξ can be calculated by the equation below:

$$\xi = \frac{h_c}{a} = \frac{la}{l + \sqrt{0.5(\sin a \cdot tg^{-1} i_0) \cdot (\frac{a}{H_0})^{0.1}}} \tag{2}$$

Where, h_c is shrinkage depth of water behind floodgate; a is height of arch gate (m); i_0 is baseboard gradient of conduit; H_0 is functional water head of water intake (m); l is length of conduit.

In line with general design criterion, $b/a \geq 1.2$ should be made. Because A_0 is too big, flow velocity behind the gate related to H_0 above should be 23～27m/s to satisfy the structural requirement.

2.2Rotating flow generator

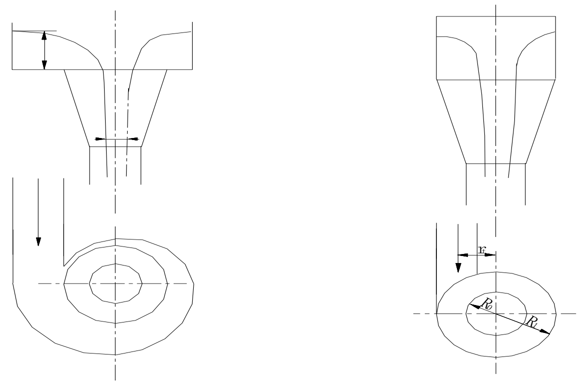
Body type of rotating parts of rotational flow shaft spillway constructed abroad is mostly similar with volute of water turbine; its major size is written in table 1.

Table 1. The size of rotating parts of rotational flow shaft spillway abroad

Project name	B (m)	H (m)	D (m)	R_t (m)	Q (m^3/s)	F_r
Santa Maria	3.00	3.50	2.60	3.45	21.6	0.35
di Monte Argento	5.50	7.86	5.50	6.05	165.0	0.41
di Grotto Companre	5.25	7.23	4.50	5.63	100.0	0.31
di Montemaggiore	3.90	4.68	3.26	4.28	40.0	0.32
di Narni	7.20	7.60	6.00	7.65	180.0	0.38
di Curbans	7.30	6.02	7.30	9.26	140.0	0.41

From table 1, it can be seen that in all existing projects, the maximum discharge amount of rotational flow shaft spillway is 180.0m3/s. Water flows before rotating parts water intake are all sub-critical flows (Froude number Fr<1.0). Because the connection between conduit and rotating parts is not tangency, the cross-section of rotating parts is relatively bigger. The structure is complicated; the distance between conduit and shaft axle wires r_t is also bigger. When discharge volume is smaller, the conduit water flow is smooth and can acquire bigger ring-directional flow speed and increase ratio of energy dissipation. However, when the discharge volume of water diversion is bigger, supercritical flow will emerge. At this time, water flow will rotate strongly, causing high internal water level of rotating parts. Moving hydraulic jump is generated in water diversion canal and no stable cavity can be created in shaft.

Consequently discharge capacity and ratio of energy dissipation are lowered greatly. For arch dam with thinner body, sub-thread tangential waterlogged rotating method is suggested which is demonstrated in figure 1. The facility structure is simple, construction is convenient, and the occupied internal space is smaller which is beneficial to the structural security of dam body.



(a) Traditional vortex water (b) Sub-thread tangential waterlogged rotating

Figure 1. Structure schematic diagram of rotational flow generator

2.3 Eccentricity distance r_t and radius of shaft R_0

Confirming eccentricity distance r_t and radius of shaft R_0 in general occasions needs to consider two principles: (1) with given functional water head, discharge volume determined by $Q_0 = \varphi_0 \xi A_0 \sqrt{2g(H_0 - \xi b)}$ is needed; (2) there must be relatively high ratio of energy dissipation.

In order to avoid harmful phenomena caused by high-speed water flow in shaft, it is more appropriate to keep the maximum flow speed in shaft within 30m/s. When the distance between water surface in shaft and baseboard of water intake is less than 50m, the target can be reached without very high ratio of energy dissipation; once the distance reaches 100m or above, very high ratio of energy dissipation is needed. So at this time the eccentricity distance r_t must be as big as possible within the structural design limitation range. To realize this, a transition section can be set up between rotating parts and shaft. The upper ends of transition section and rotating parts have equal diameters. The lower end is connected to shaft. Then the radius of rotating parts R_1 is bigger than radius of shaft R_0 and bigger eccentricity distance r_t can be acquired.

For the purpose to acquire the maximum discharge volume Q_{max} that can get through internal shaft with given r_t, R_0 and functional water head, suppose under conditions of no energy lost from rotating parts, the following relational expressions are obtained according to angular momentum theory and Bernoulli's equation:

$$v_m = \mu\sqrt{2gH_0'} \tag{3}$$

$$H_0' = \varphi_0^2 \xi^2 (H_0 - \xi b) + \xi b \tag{4}$$

$$Q_{max} = v_m \pi R_0^2 \tag{5}$$

$$\upsilon_z = \upsilon_m / \omega \quad , \quad \upsilon_{\theta,R} = S\upsilon_m \tag{6}$$

$$\mu = 1/\sqrt{S_0^2/(1-\omega_c) + 1/\omega_c^2} \tag{7}$$

$$\omega = 1 - (r_G / R_0)^2 \tag{8}$$

$$S_0 = \pi R_0 r_t \sin(b/\xi A_0) \tag{9}$$

Where, v_m is virtual flow direction speed in shaft; μ is velocity coefficient corresponded to v_m when critical flow emerges in shaft entrance; v_z , $v_{c,R}$ are cross-sectional average flow speed of actual flow direction and ring-directional flow speed on shaft internal wall surface; ω is area of relative cross section of passage; r_G is gas cavity radius of spiral flow center; c is subscript representing critical state; s_0 is initial rotating parameter. ω_c is determined by $1 - S_0^2\omega_c^3 / 2(1-\omega_c)^2 = 0$ in which $S_0^2\omega_c^3 / 2(1-\omega_c)^2$ is the square of propagation velocity and water flow directional speed specific value of surface turbulence at the critical fracture surface. The flow is race if the specific value is smaller than 1, critical flow if it equals to 1 and slow flow if it is bigger than 1.

r_t and R_0 are calculated jointly by equations (3) to (9).

Under supercritical flow conditions, in order to ensure that shaft is cavity rotational flow, diameter of shaft can also be calculated by empirical equation (10):

$$D = k(Q^2/g)^{0.2} \tag{10}$$

2.4 Cushion pool and horizontal outlet

Shaft should be connected to the fracture surface of horizontal outlet entirely. There is cushion pool in the lower part. Make diameter of horizontal outflow outlet D' equal with diameter of shaft D and cushion pool diameter equal with shaft diameter, then the effects of water flow in shaft have on horizontal outflow outlet will be minimized to ensure that a more stable water flow regime in outflow outlet is maintained. Cushion pool is mainly used to keep a certain buffer layer to prevent baseboard from being eroded by initial falling water in addition to energy dissipation. Besides, pier for rotation resistance can be set in cushion pool to dissipate energy, prevent vibration and improve flow regime within the outlet. And it is also useful for reinforcing baseboard.

When downstream water level is lower than horizontal outflow outlet top, the outlet becomes un-submerged outflow outlet; conversely, when downstream water level is higher than outlet top, discharge outlet becomes submerged outflow outlet. Exit cross-sectional area is controlled by gradually changing method at the discharge outlet for the purpose of controlling outlet velocity and keeping flow speed away from flow speed range within which no harmful secondary phenomena occur.

3. MODELING TEST

3.1 Model design

Suppose the height of an arch dam is 300m and that of internal rotational flow shaft spillway intake head is 40m; conduit section bottom slope is plain; the difference of water levels of upstream and downstream is 210m. According to design criterion and requirements mentioned above, scheme design of rotational flow shaft spillway is conducted. In order to verify the rationality of the design scheme, hydraulic modeling test is conducted to the scheme. The testing model of rotational flow shaft spillway is an undistorted model designed in line with gravity similarity criterion with linear ratio being λ =1/150 and model length being 13m, width being 2m, including upstream measuring weir, flat water segment, reservoir, water inlet section, rotating parts, tapered segment, shaft segment (plug included), water-pillow segment, outflow segment and water return conduit etc. Sizes of each part of internal rotational flow shaft spillway are listed in table 2.

Table 2. The sizes of rotational flow shaft spillway

Water inlet	Rotational flow generator		transition section	shaft	cushion pool	Water outlet
a×b(m)	eccentricity distance r_t	diameter R_1	upper ends diameter	diameter	diameter	diameter
10×12m	8.0m	27.0m	27.0m	16.0m	16.0m	16.0m

3.2 Testing scheme

In order to test the rationality and the scientific nature of designed scheme and analyze features of water discharge and energy dissipation of rotational flow shaft, the model conducted tests of 5 schemes in terms of water in flow conditions, plug layout situation, water outflow conditions and so on. The testing scheme is as demonstrated in table 3.

Table 3. The schemes of model test

Scheme	Mode of water inlet	1#Plug (cm)	2#Plug (cm)	3#Plug (cm)	Mode of water outlet
Scheme Ⅰ	Pressure flow and tangential inlet	9.33	9.33	9.33	Non pressure and un-submerged outflow
Scheme Ⅱ	Non pressure flow and tangential inlet	9.33	9.33	9.33	Non pressure and un-submerged outflow
SchemeⅢ	Non pressure flow and tangential inlet	9.33	6.67	9.33	Non pressure and un-submerged outflow
SchemeⅣ	Non pressure flow and tangential inlet	9.33	8.00	9.33	Pressure flow and un-submerged outflow
Scheme Ⅴ	Non pressure flow and tangential inlet	9.33	8.00	9.33	Pressure flow and submerged outflow

3.3 Discharge capacity

The relational curve of upstream functional water head and discharge volume is acquired through modeling tests of 5 schemes. It is demonstrated in figure 2.

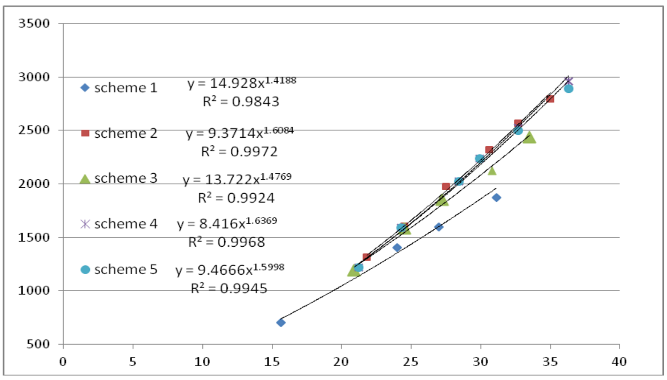


Figure 2. The relational curve of upstream functional water head and discharge volume

From the discharge capacity curve of each scheme above, it can be seen that: 1) when water intake functional water head is 20m, discharge capacity of all rotational flow shaft spillway exceeds 1000m3/s; when it is 30m, discharge capacity reaches 2000m3/s; rising trends of discharge capacity of each scheme along with water head is better; 2) from the fitted curve, discharge capacity of each scheme is basically in direct ratio with 1.5th power of intake head; slight differences exist between each scheme while Scheme Ⅳ has the biggest and Scheme Ⅰ has the smallest; 3) the reason why discharge capacity of Scheme Ⅲ is smaller than that of Scheme Ⅱ and Scheme Ⅳ is the diameter of its 2#plug is smaller, thus the water-pillow formed by water flow at this part is higher and gets through the above parts of 2#plug very quickly, affecting its discharge volume; 4) from the perspective of discharge capacity, Scheme Ⅱ, Scheme Ⅳ and Scheme Ⅳ are better; when water intake functional water head is 35m, discharge capacity reaches 2800m3/s, three schemes all have big flow discharging potential; 5) Scheme Ⅴ is the submerged outflow situation of Scheme Ⅳ at downstream; the difference between discharge capacity of two schemes is not big which means that Scheme Ⅳ still has bigger discharge capacity under conditions of downstream being submerged. Thus with consideration of discharge capacity, Scheme Ⅳ is the primary choice and Scheme Ⅱ is the secondary.

3.4 Ratio of energy dissipation

The calculation of ratio of energy dissipation is mainly based on the measurement of lower outlet velocity and pressure and then construction of energy equation with inflow and outflow water flows. Through modeling tests of 5 schemes, the relations between different upstream functional water heads, discharge volume and ratio of energy dissipation are acquired as demonstrated in table 4.

Table 4. Ratio of energy dissipation of each scheme

Scheme Ⅰ			Scheme Ⅱ			Scheme Ⅲ			Scheme Ⅳ			Scheme Ⅴ		
water heads /m	discharge volume /m³/s	ratio of energy dissipation /%	water heads /m	discharge volume /m³/s	ratio of energy dissipation /%	water heads /m	discharge volume /m³/s	ratio of energy dissipation /%	water heads /m	discharge volume /m³/s	ratio of energy dissipation /%	water heads /m	discharge volume /m³/s	ratio of energy dissipation /%
15.6	703	98.2%	21.8	1314	93.7%	20.9	1193	94.8%	21.2	1221	94.6%	21.2	1218	94.6%
21.0	1190	94.9%	24.5	1604	90.8%	24.5	1582	91.0%	24.3	1590	91.0%	24.3	1587	91.0%
24.0	1405	92.9%	27.5	1976	86.2%	27.2	1855	87.9%	28.4	1998	86.0%	28.4	2023	85.6%
27.0	1596	91.0%	30.6	2320	81.2%	30.3	2122	84.3%	29.9	2238	82.5%	29.9	2235	82.5%
30.6	1874	87.8%	32.7	2568	77.2%	33.5	2439	79.5%	32.7	2521	78.0%	32.7	2497	78.5%
36.8	2149	84.3%	35.0	2794	73.3%	36.0	2768	73.2%	36.3	2960	70.2%	36.3	2888	71.6%

4. HYDRAULIC CHARACTERISTICS

4.1 Rotating flow generator without a tapered segment

Internal rotational flow shaft in the application as spillway must have certain discharge capacity. This is precondition of it being popularized and applied. When tapered segment is not set under rotating flow generator, height of tapered segment equals with zero. It is relatively simpler, and there is already some experimental data abroad. At this time expression of discharge volume Q can be written as:

$$Q = \mu_0 \pi R^2 \sqrt{2g(h+\delta)} \tag{11}$$

$$Q = \mu \pi R^2 \sqrt{2g(h+\delta)+v_0^2} = \mu \pi R^2 \sqrt{2gh_v} \tag{12}$$

Where, discharge volume coefficient μ_0 already considered the effects of near velocity v_0 while discharge volume coefficient μ is not included in the effects of near water velocity.

To calculate discharge volume in different situations using limited experimental data, a reference system is brought in. It is a rotational flow shaft that has geometric similarity with radius of shaft being 1 dm. Its discharge volume is the referred discharge volume Q_r. If radius of the actual shaft is R, taking reference system as model, then the ratio is $\lambda_l = R(dm)/1$, relation between actual discharge volume Q_P and referred discharge volume Q_r can be expressed as $(Q_P/Q_r)^{2/5} = \lambda_l$. Convert the experimental results into referred discharge volume. The referred discharge volume and discharge volume coefficient acquired are listed in table 5.

Table 5. The referred discharge volume and discharge volume coefficient

number	Q_P (m³/s)	Q_r (m³/s)	μ_0
1	703	4.24	0.370
2	1190	7.18	0.482
3	1405	8.47	0.530
4	1596	9.62	0.570
5	1874	11.30	0.652
6	2149	12.96	0.748

The fitted curve of referred discharge volume and referred discharge volume coefficient is shown in figure 3.

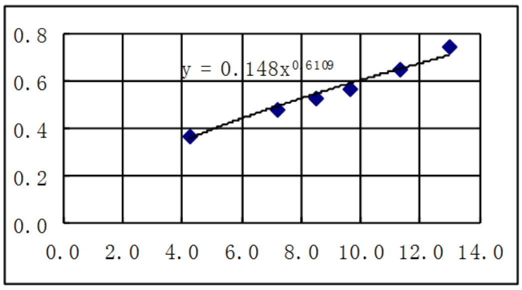


Figure 3. The curve of referred discharge volume and referred discharge volume coefficient

From experimental results, empirical correlation of μ_0 and Q_r is:

$$\mu_0 = 0.148 Q_r^{0.6109} \tag{13}$$

The front depth of water of rotating parts h can be derived from discharge volume equation (13) as:

$$h = R\left[\frac{1}{2gR}\left(\frac{Q}{\mu_0 \pi R^2}\right)^2 - \frac{\delta}{R}\right] \tag{14}$$

Solve jointly equation (14), expression of water diversion segment width b is:

$$b = \frac{\pi R^2}{h\sqrt{\frac{1}{\mu^2} - \frac{1}{\mu_0^2}}} \approx \frac{\mu \pi R^2}{0.224h} \tag{15}$$

In order to find out relations between distances Δ of shaft axis and water diversion segment center line and other parameters, theorem of momentum can be similarly applied.

At the front intake outlet cross-section of rotating parts, angular momentum of fluid to shaft axis K_1 is

$$K_1 \approx \rho Q v_0 \Delta = \rho Q^2 \Delta / bh \tag{16}$$

where, ρ is density of water.

Suppose that the ring-directional flow speed v_t and vertical velocity v_z at the shaft entrance are constants, and then angular momentum at the shaft entrance K_2 is:

$$K_2 = \rho \int_{r_g}^{R} 2\pi r^2 v_z v_\theta dr = \frac{2\rho Q v_\theta R(1 - r_{g_0}^{*3})}{3(1 - r_{g_0}^{*2})}, \; r_{g_0}^* = \frac{r_{g_0}}{R} \tag{17}$$

It is derived from momentum balance $K_1 = K_2$ that:

$$\rho Q^2 \Delta / bh = \frac{2\rho Q v_\theta R(1 - r_{g_0}^{*3})}{3(1 - r_{g_0}^{*2})} \tag{18}$$

Simplified as: $$\Delta = \frac{2bhv_\theta R(1 - r_{g_0}^{*3})}{3Q(1 - r_{g_0}^{*2})} \tag{19}$$

4.2 Rotating flow generator with a tapered segment

The calculation of rotational flow shaft spillway discharge capacity of rotating parts with a tapered segment in generally in the following form:

$$Q = \mu_c \pi R_w^2 \sqrt{2g(h + h_c) + V_0^2} \tag{20}$$

Where, μ_c is discharge volume coefficient of rotational flow shaft spillway with a tapered segment; h is depth of water at the water intake of rotating parts; V_0 is relative flow speed; h_c is height of tapered segment; R_w is radius of shaft. In this test, plug is added into the shaft, so plug factor should be considered. Suppose an average radius of shaft is used here, so R_w is shaft average radius which is

$$R_w = \frac{16 \times 80 + 14 \times 30}{110} \times \frac{1}{3} = 5.15cm \cdot$$

This test conducted tests for several schemes but here only scheme 1 is verified, that when h_c =20cm, R_w =5.15cm, discharge volume and discharge volume coefficient are listed in table 6.

Table 6. The discharge volume and discharge volume coefficient of the scheme Ⅰ

Water head(cm)	10.41(cm)	14.01(cm)	16.01(cm)	18.01(cm)	20.71(cm)	24.31(cm)
$Q(l/s)$	2.55	4.32	5.10	5.79	6.80	7.80
μ_c	0.127	0.207	0.240	0.268	0.306	0.339

In order to build up expression for discharge volume coefficient, situation of rotating parts without a tapered segment needs to be considered first. In this situation, discharge volume calculation can adopt the following formula.

$$Q = \mu \pi R_w^2 \sqrt{2g(h + \delta) + V_0^2} \tag{21}$$

Apply angular momentum theory, at the cross-section of rotating part water intake, get a discharge volume infinitesimal near the free water surface ΔQ, its angular momentum to shaft axis K_1 is:

$$K_1 = \int \Delta m \cdot V \cdot x = \int \rho \Delta h \cdot V^2 x dx = \rho \Delta h \cdot V^2 b \cdot \Delta = \rho \Delta Q \cdot V \cdot \Delta \tag{22}$$

Angular momentum of this discharge volume infinitesimal at shaft entrance K_2 is:

$$\begin{aligned} K_2 &= \int \Delta m \cdot V_T \cdot T = \int \rho 2\pi r \Delta r \cdot V_Z \cdot V_T \cdot T = 2\pi \rho V_Z \cdot V_T \int r^2 dr \\ &= \frac{\Delta Q}{\pi(R_w^2 - r_g^2)} \cdot V_T \rho \frac{2\pi}{3}(R_w^3 - r_g^3) \end{aligned} \tag{23}$$

Among the equation, V_T means tangential velocity.

Since $K_1 = K_2$, then:

$$V \cdot \Delta = \frac{2}{3} V_T \frac{1 - R_*^3}{1 - R_*^2} R_w \tag{24}$$

Where, $R_* = r_g / R_w$.

At the cross-section of shaft entrance, relation between overall velocity V, tangential velocity V_T and vertical velocity V_Z is:

$$V_T = (V^2 - V_Z^2)^{\frac{1}{2}} = [\frac{Q}{\mu^2\pi^2 R_w^4} - \frac{Q^2}{\pi^2(R_w^2 - r_g^2)^2}]^{\frac{1}{2}}$$

$$= \frac{Q}{\pi R_w^2 \mu} \cdot \sqrt{1 - \frac{\mu^2}{(1-R_*^2)^2}} \quad (25)$$

From these equations above it can be derived that:

$$\frac{bh}{\pi R_w \cdot \Delta} = \frac{3}{2}\frac{1-R_*^2}{1-R_*^3}\frac{\mu}{\sqrt{1-\frac{\mu^2}{(1-\frac{\mu^2}{(1-R_*^2)^2}}}} \quad (26)$$

Make $\Phi = \frac{bh}{\pi R_w \Delta}$, which reflects geometric parameter of shaft body type. Then according to experimental results it can be derived that:

$$R_* = 0.8801 - 1.6866\mu^2 \quad (27)$$

Then it is confirmed that relation of μ and Φ without tapered segment is:

$$\Phi = 1.5\frac{1-(0.8801-1.6866\mu^2)}{1-(0.8801-1.6866\mu^2)^3}\frac{\mu}{\sqrt{1-\frac{\mu^2}{[1-(0.8801-1.6866\mu^2)^2]^2}}} \quad (28)$$

This equation is bit complicated, for convenience, the relation between μ and Φ is demonstrated in figure 4:

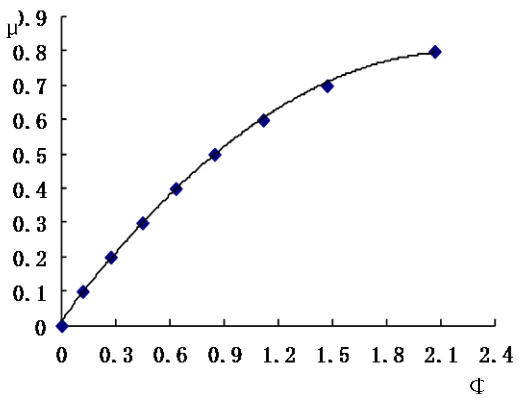


Figure 4.The relationship curve of φ～μ

For the purpose to translate discharge volume coefficient without tapered segment into discharge volume coefficient with conical gradual shrinkage tapered segment, the following equation is used to express discharge volume of the latter one:

$$Q = \mu_c' \pi R_c^2 \cdot \sqrt{2g(h+\delta)+V_0^2} = \mu_c' \pi R_c^2 \sqrt{2gH_v} \quad (29)$$

Same expression equation is also used in expressing situation without tapered segment but replace μ and R_w with μ_c' and R_c. Obviously, with given dimensionless parameter Φ, μ can be calculated directly.

6. CONCLUSIONS

Rotational flow shaft spillway can meet hydraulic conditions of different intake and outtake water outlets. From the perspectives of discharge volume and ratio of energy dissipation, rotational flow shaft spillway is able to meet large discharge volume and high energy dissipation effect requirements at the same time. It is suited to be constructed in high arch dam with high water head, large discharge amount and deep canyon for the purpose of flood discharge and energy dissipation. Discharge capacity of rotational flow shaft spillway increases along with increase of water intake functional water head. When water intake functional water head is 35m, discharge capacity can reach 2800m^3/s. Ratio of energy dissipation of rotational flow shaft spillway decreases along with increase of discharge volume. When discharge volume reaches approximately 3000m^3/s, ratio of energy dissipation is still higher than 70%. Discharge capacity of rotational flow shaft spillway with transition section is related to geometric features of tapered segment and hydraulic conditions. When height of tapered segment reaches certain degree, difference value of R_w and R_c is smaller and it is closer to situation without tapered tube. If values of R_w and R_c are given, then as h_c increases, it is closer to situation without tapered tube; under condition of R_w, R_c, h_c being fixed, as depth of water of rotating parts decreases, water layer of lower discharge flow is thinner, impact of tapered segment is smaller and it is closer to situation without tapered segment.

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