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The Research On The Internal Flow Pattern Characteristics Of Steep Slope Tunnel

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THE RESEARCH ON THE INTERNAL FLOW PATTERN CHARACTERISTICS OF STEEP SLOPE TUNNEL

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Abstract: More and more steep-grade tunnels are applied to the hydroelectric development of the mountain rivers. The related research and prototype operation show that the hydraulic characteristics of steep slope tunnel, such as discharge capacity, flow pattern, flow pressure etc. are different from that of slight slope tunnel. In the article, based on the model test data of steep slope tunnels in a lot of hydropower stations, the reasons why there are hydraulic characteristics difference existing between steep slope tunnel and slight slope tunnel are analyzed, especially about the influencing factors of alternation of free and pressure flow and the related control measures. The research results show the influencing factors include relative submerge depth H/a, the tunnel shape (bottom slope, inlet top shape, tunnel height, tunnel length, bending section, gate shaft etc.), inlet guiding channel arrangement and the consequent air suction swirl etc. According to the terrain condition, geological condition, project function, operation safety and economic factor etc., some measures can be adopted to improve the mixed alternation of free and pressure flow problems in steep slope tunnels.
Key words: steep slope tunnel, flow pattern in tunnel, alternation of free and pressure flow, influencing factor, the improving measures.

1 .ORIGIN OF THE PROBLEMS

There are abundant hydraulic energy resources in mountain rivers. In the recent years, in order to exploit hydraulic energy resources adequately, more and more hydropower projects in China and abroad are determined to build in mountain rivers where the valley is narrow, riverbed slope is steep and both riverside are sheer. These projects mostly adopt tunnels as their diversion structures according to the terrain and geological conditions. Due to great riverbed slope, the choices of the inlet and outlet elevation of the tunnels in some projects are limited, which results in steep bottom slope and long tunnel length, viz. steep slope tunnels ($i > i_k$, i refers to bottom slope, i_k refers to critical slope.). The diversion tunnel parameters of some mountain hydraulic projects in China and abroad are listed in Table 1.
As listed in Table 1, due to the steep slope grade, the hydraulic characteristics of steep slope tunnel, such as discharge capacity, flow pattern etc. are different from that of slight slope tunnel. For general slight slope tunnel, its discharge capacity is very stable, there are three kinds flow pattern of free flow, half pressure flow and full pressure flow which appear inside the tunnel. However, there is the fourth flow pattern of alternation of free and pressure flow inside steep slope tunnel and the discharge section of this flow pattern is great. As shown in Table 1, take the diversion tunnels of a certain hydropower project to serve as example in Malaysia[1][2][3],

alternation of free and pressure flow happens in 1# tunnel (bottom slope of 3.19%) and 2# tunnel (bottom slope of 2.87%) respectively in the discharge conditions of Q=2300~3670m3/s and Q=2800~3400m3/s, the correspondent discharge ranges is 1370m3/s and 600m3/s respectively, with inhaling whirlpools appearing at the inlets and air intake phenomenon happening in the gate shafts. The discharge capacity of steep slope tunnel is also unstable and easy to be effected by flow pattern of the inlet and the tunnel body. Taking the diversion tunnel of a certain project to serve as example in Irrawaddy of Myanmar[4], whose bottom slope grade is 7.5% as shown in Table 1, due to the inlet top of ellipse form, the discharge section of alternation of free and pressure flow is great, different flow pattern happens respectively inside the tunnel during the process of rising reservoir level and the process of falling reservoir level, resulting in different reservoir level in the condition of the same discharge.

Table 1 Diversion tunnel parameters of some project on mountain rivers in China and abroad

Project	Nation/River	Dam form	Diversion buildings	Design discharge Q(m^3/s)	Tunnel length(m)	Design bottom Slope(‰)	Section form	Section dimension B×H(m×m)
Wudongde	China/Jinsha	dome dam	tunnel	26600	1430~1680	5.6~12.4	city-gate section	12×16 /16.5×24
Baihetan	China/Jinsha	dome dam	tunnel	26800	1600~2050	1.9~19.9	city-gate section	17.5×22.0
Xiluodu	China/Jinsha	dome dam	tunnel	32000	1260~1940	2.8~10.6	city-gate section	18×20
Pubugou	China/Daduhe	core rockfill dam	tunnel	7320	920~1000	5.0~5.4	horseshoe	13×16.5
Jingpin first class	China/Yalongjiang	dome dam	tunnel	10000	1200	3.8~3.9	city-gate section	15×21
A project	Malaysia	CFRD	tunnel	3044	642~783	31.9/28.7	horseshoe	10×10.9
A project	Myanmar/Irrawaddy	gravity dam	tunnel	286	1124	75	city-gate section	5×6

So the hydraulic characteristics of steep slope tunnel are different from that of slight slope tunnel, especially alternation of free and pressure flow is disadvantageous to the project safety. The phenomenon of alternation of free and pressure flow is a kind of unstable flow pattern which happens in the tunnel, with air intake whirlpool at the inlet, unstable air bag in the water body and the periodic pressure change of free flow and pressure flow inside the tunnel. This flow pattern can result in the periodic change of pressure distribution, flow velocity and discharge inside the tunnel. The great negative pressure and flow velocity can bring cavitation damage, vibration damage and impact damage to the tunnel. The unstable flow pattern trends to be avoided in the hydraulic design and project operation. The related hydraulics problems about steep slope tunnel appear gradually with the development of mountain river projects and the related research data is rare at the present time. Therefore, according to the related theory and based on the model test results, the internal flow characteristics of steep slope tunnel are explored and analyze in this article.

2. THE ANALYSIS ON THE INTERNAL FLOW PATTERN CHARACTERISTICS OF STEEP SLOPE TUNNEL

The internal flow pattern of diversion tunnel is related to the inlet submergence. When downstream level is high and the outlet top is submerged (submerged discharge condition), pressure flow happens inside the tunnel and the discharge capacity of the tunnel is reduced. In the condition of lower downstream level and free outflow near the outlet, flow pattern inside the tunnel is complex. The following analysis will focus on the free outflow condition.

2.1 The effect of reservoir level on flow pattern inside the tunnel

2.1.1 Slight slope tunnel

For slight slope tunnel ($i < i_k$), if $H / a < k_1$ (H refers to water depth above the elevation of the inlet bottom plate of the tunnel, a refers to tunnel height and k_1 is a constant number.), free flow appears in the tunnel. If $k_1 < H / a < k_{2m}$ (k_{2m} is a constant number.) and the tunnel length is short, half pressure flow appears in the tunnel with the inlet top of sharp-edged form, the inlet is submerged and free flow happens in the tunnel body. If the tunnel is long, half pressure flow appears in the tunnel with the inlet top of sharp-edged form or curving form, pressure flow happens in the section near the inlet and free flow happens in the rest of the tunnel body. If $H / a > k_{2m}$, pressure flow appears in the whole tunnel.

2.1.2 Steep slope tunnel

The internal flow patterns inside steep slope tunnel ($i > i_k$) are shown in Figure 1[5]. If $H / a < k_1$, free flow appears in the tunnel, as shown in Figure 1(a). If $k_1 < H / a < k_{2s}$ (k_{2s} refers to a constant number.), when normal water depth $h_0 > a$ and the tunnel is short or $h_0 < a$, half pressure flow appears in the tunnel with the inlet top of sharp-edged form, the inlet is submerged and free flow happens in the tunnel body, as shown in Figure 1(b). If $k_1 < H / a < k_{2s}$, $h_0 > a$ and the tunnel is long, the periodic flow pattern (alternation of free and pressure flow) appears in the tunnel the inlet top of sharp-edged form or curving form, unstable air bags are observed in the water body, as shown in Figure 1(c). When $H / a > k_{2s}$ due to upstream level rising, pressure flow appears in the whole tunnel, as shown in Figure 1(d). So it can be seen that the additional flow pattern of alternation of free and pressure flow is the only difference between slight slope tunnel and steep slope tunnel.

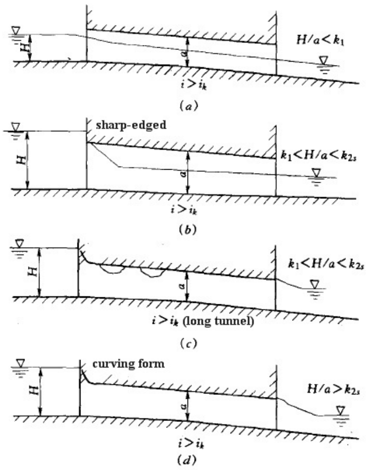


Figure 1 The schematic drawing of flow pattern in the tunnel under the condition of free flow

2.1.3 Threshold values of flow transformation

k_1, k_{2m} and k_{2s} mentioned above are defined as threshold values of flow transformation.

(1) The constant number k_1 is the threshold value between free flow and half pressure flow, which is related to bottom slope of the tunnel, discharge, both side wall form of the inlet, the form and dimension of tunnel section. It can be determined by experiment. For diversion tunnel, the inlet form is the main influencing factor of k_1 value. The value of k_1 ranges from 1.1 to 1.3, with the minor value adopted when local head loss coefficient of the inlet sidewall is bigger, vice versa. The value of k_1 adopts 1.2 as the threshold value generally.

(2) The constant number k_{2m} is the threshold value between half pressure flow and pressure flow in slight slope tunnel.

$$k_{2m} = 1 + \frac{1}{2}(1 + \sum \xi + \frac{2gl}{C^2 R})\frac{v^2}{ga} - i\frac{l}{a} \qquad (1)$$

In the equation, $\sum \xi$ refers to the sum of local head loss coefficient from the inlet to the outlet, C refers to Chezy coefficient, R refers to hydraulic radius in the condition of full flow passing through the tunnel. v^2 / ga is the squared value of Froude number at the outlet section, which is equal to 1.62 when the outlet section is surrounded by air. If bottom plate extends from the outlet section, considering critical water depth $h_k = a$, the value of v^2 / ga is equal to 1.

(3) The constant number k_{2s} is the threshold value between unstable flow pattern and pressure flow in steep slope tunnel, which is determined by experiment. The mean value of 1.5 is always adopted as the value of k_{2s} in the hydraulic project design. If $1.2 < H / a < 1.5$, flow pattern is defined as half pressure flow or unstable flow. If $H / a > 1.5$, flow pattern is defined as pressure flow.

2.2 Flow pattern affected by the tunnel form

In the above analysis of flow pattern affected by reservoir level, the influencing factors have included some parameters of tunnel form, such as bottom slope, tunnel length, inlet form and tunnel height etc. Here the effect of these parameters on flow pattern inside the tunnel will be introduced.

2.2.1 Flow pattern affected by the tunnel slope grade

According to 2.1, the smooth transition of flow pattern from pressure flow to half pressure flow to free flow or its reverse transition is only possible for slight slope tunnel [6]. For steep slope tunnel, if $1.2 < H / a < k_{2s}$, $h_0 > a$ and the tunnel is long, alternation of free and pressure flow will happen in the tunnel with the inlet top of sharp-edged form or curving form. So the tunnel slope grade is a key factor to the forming of alternation of free and pressure flow.

2.2.2 Flow pattern affected by the inlet form of the tunnel

There are two types of sharp-edged form and curving form for the inlet top of tunnel. For steep slope tunnel, if $1.2 < H / a < k_{2s}$ and $h_0 < a$, the discharge capacity and flow pattern inside the tunnel with the inlet top of sharp-edged form are obviously different from that of the tunnel with inlet top of curving form. For the inlet top of sharp-edged form, half pressure flow pattern results in the lower discharge capacity of the tunnel. For the inlet top of curving form, alternation of free and pressure flow increases the discharge capacity of the tunnel.

2.2.3 Flow pattern affected by the tunnel height

According to 2.1, the effect of tunnel height a on flow pattern of the tunnel is closely related to normal water depth h_0 and tunnel length l. If $1.2 < H / a < k_{2s}$, when $h_0 > a$ and the tunnel is long, alternation of free and pressure flow will happens in the tunnel; when the tunnel is shorter, half pressure flow will happens in the tunnel. When $h_0 < a$, half pressure flow will happens in the tunnel with the inlet top of sharp-edged form, alternation of free and pressure flow may happen in the tunnel with the inlet top of curving form.

2.2.4 Flow pattern affected by the length of the steep slope tunnel

The threshold value of steep slope tunnel length l_{ks} affects flow pattern greatly. For steep slope tunnel with the inlet top of sharp-edged form, if $1.2 < H / a < k_{2s}$, normal depth $h_0 > a$ and $l < l_{ks}$, half pressure flow happens in the tunnel, as shown in Figure 1(b); if $l > l_{ks}$, alternation of free and pressure flow happens in the tunnel, as shown in Figure 1(c).

The value of l_{ks} is determined by Equation (2):

$$l_{ks} = l_i + l_s + l_0 \qquad (2)$$

In the equation, the meanings of l_i , l_s and l_0 are shown in Figure 2. $l_i = 4a$; $l_0 = 0 \sim 0.5a$, it can be neglected generally. The value of l_s can be calculated by segmentalion seeking solution according to water surface line of C2 type. The value of h_c can be calculated by Equation (3)

$$\frac{h_c}{a} = 0.037\frac{H}{a} + 0.573\mu + 0.182 \qquad (3)$$

In the equation, μ refers to discharge coefficient and is determined by the inlet form, as shown in Table 2.

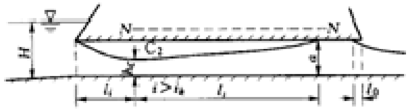
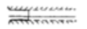
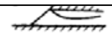
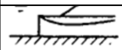
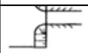
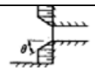


Figure 2 Half pressure flow in the steep slope tunnel

Table 2 Discharge coefficient and side contraction coefficient of flow at the inlet

The in;et form	Figure	Discharge coeffiicient μ	side contraction coefficient of flow at the inlet η
Corridor type		0.576	0.715
Collar type		0.591	0.726
The inlet extending from the filling slope		0.596	0.726
The cone inlet with the side slope grade of 1:1~1:1.5		0.625	6 .735
The trumpet inlet with submerged side wall and the filling side slope grade of 1:1.5 (θ=30°)		0.670	0.740

For the inlet forms such as vertical tunnel face, sharp-edged, circular bead or oblique angle, the section form of the tunnel body such as rectangle or round, with the concrete surface, the value of threshold length l_{ks} can be calculated roughly according to the curving as shown in Figure 3, no matter wing wall or not, no matter slight slope or steep slope.

2.2.5 Flow pattern affected by the curving section of the tunnel

According to the related research[6], for straight tunnel, when H/a =1.1~1.5, alternation of free and pressure flow happens. For curving tunnel, when H/a=1.1~1.5, alternation of free and pressure flow happens. So the operation level section of curving tunnel in which alternation of free and pressure flow happens is much bigger than that of straight tunnel.

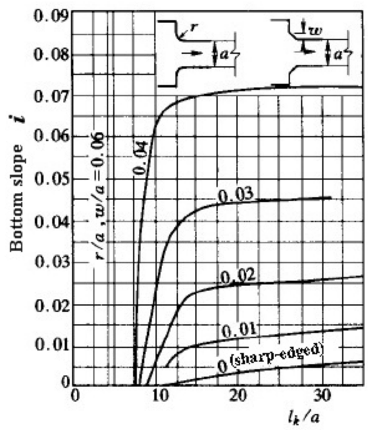


Figure 3 The relationship curve of i and lk/a

2.2.6 Flow pattern affected by the phenomenon of air intake in gate shaft

Gate shafts are set up behind the inlet transition in some hydraulic project, like a certain project in Malaysia. The related model test results show that negative pressure appears at the inlet top of steep slope tunnel[1][2]. Bad curving design of the inlet top increases negative pressure, which results in the phenomenon of air intake in gate shaft and increases the discharge range of alternation of free and pressure flow.

2.3 Flow pattern affected by whirlpool at the inlet

The inlet of diversion tunnel is generally located at the side of river bed. Due to dissymmetric flow moving at the inlet, whirlpools appear when the inlet submergence reaches to some extent. There are four kinds of whirlpool, such as surface whirlpool, whirlpool with air intake intermittently, piercing whirlpool with air intake intermittently and piercing whirlpool with air intake steadily. Surface whirlpool hardly affects flow pattern inside the tunnel. Whirlpool with air intake brings much air into the tunnel, air bag forms gradually with air volume increasing. Unstable air bag changes its form and dimension when it is pushed to move along the tunnel by flow, which make flow pattern become unstable and may increase the discharge range of alternation of free and pressure flow.

For the determination of diversion tunnel arrangement and tunnel form, whirlpool form is related to submergence level at the inlet and diversion tunnel dimension. According to the model test of diversion tunnel for Jiangpinghe hydropower station by CRSRI, if relative submergence depth $H/a < 1.15$, surface whirlpool happens with the occasional appearance of air intake funnel. If $1.15 < H/a < 2.80$, pulsatile air intake whirlpool happens with the followed piercing whirlpool with air intake. If $H/a > 3.08$, shallow whirlpool happens again with the occasional appearance of air intake funnel. The relative submergence depth section of air intake whirlpool matches that of alternation of free and pressure flow. Therefore air intake whirlpool is an important factor to the forming of alternation of free and pressure flow.

2.4 Flow pattern affected by the inlet guiding channel arrangement

The tunnels of a certain hydraulic project are located at the left bank of river bed in Malaysia. Due to dissymmetric flow moving at the inlet and the inlet top platform extending from the mountain body, great flow moving space created by submergence helps the forming of whirlpool with air intake. The air is brought into the tunnel, which aggravates flow instability and increases the discharge range of alternation of free and pressure flow.

3. The improving measures against alternation of free and pressure flow in steep slope tunnel

According to the above analysis, the main influencing factors of alternation of free and pressure flow include bottom slope, inlet form, tunnel height, tunnel length, curving section, gate shaft arrangement, operation level, air intake whirlpool caused by the dissymmetric inlet arrangement and air intake from gate shaft caused by negative pressure at the inlet top etc. Some factors such as bottom slope, tunnel length, curving section arrangement and operation level range are determined according to the special terrain condition, geological condition, project requirement and economic consideration, which cannot be changed too much. Therefore the measures against alternation of free and pressure flow in steep slope tunnel focus on vortex suppression, preventing air intake in gate shaft and the optimizing of the inlet form.

3.1 The measures of vortex suppression

In order to prevent whirlpool appearing or reduce the whirlpool intensity, the practicable measures should base on the analysis of whirlpool origin.

3.1.1 The origin of whirlpool forming and the measures of vortex suppression

The key factors of whirlpool forming include relative submergence depth H/a, dissymmetric inlet arrangement, enough space and inlet form etc. Operation level connects closely to discharge capacity of the tunnel, project cost and later operation requirement etc. If the discharge range of air intake whirlpool is greater, it can be reduced by changing the height-width ratio and discharge capacity. Dissymmetric inlet arrangement and greater flow moving space also trigger whirlpool forming. According to the related experiment research, symmetric inlet arrangement can improve incoming flow condition, which is an effective measure to suppress whirlpool at the inlet. In addition, some special structures such as eddy-eliminating beam (plate), stilling fence can crash whirlpool, which are hardly adopted due to difficult construction condition and expensive building cost compared with the limited operation period of diversion tunnel.

3.1.2 The experiment about the measures of vortex suppression

The measures of vortex suppression are explored and researched by the model test on construction diversion for a certain project in Malaysia. With limited terrain and geological condition, the inlet s of 1# and 2# tunnel adopt dissymmetric arrangement. Due to side flow effect, whirlpool with air intake forms at the right side of the inlet in the condition of lower upstream level. After the inlet top platform is submerged under the water, whirlpool still exists. Due to the inlet top platform extending far from the mountain body, great flow moving space created by submergence increases the intensity of whirlpool with air intake. Therefore the measures of vortex suppression are explored by the optimizing of the dissymmetric inlet and the reduction of flow moving space. For 1# and 2# tunnel, both inlet arrangements become symmetric by the separation of symmetric guiding walls. In the meantime, the separating wall is built on the inlet top platform. These measures reduce the flow moving space and reduce the intensity of whirlpool with air intake. For 1# and 2# tunnel, their discharge range of alternation of free and pressure flow reduces from 1370m3/s and 600m3/s to 300m3/s respectively. The improving effect of flow pattern is obvious.

3.2 Preventing air intake in gate shaft

The model test result on construction diversion for a certain project in Malaysia shows that when the gate shaft is open to air and partial measure of vortex suppression is adopted, after the inlet top platform is submerged to some extent under reservoir level, due to negative pressure effect, air intake phenomenon happens in the gate shaft aside from air-out, which aggravates alternation of free and pressure flow inside the tunnel. Air intake in gate shaft is caused by great negative pressure inside the tunnel, so closed gate shaft may prevent air intake and reduce discharge section of alternation of free and pressure flow, increased negative pressure value aggravates the pressure characteristics of the tunnel body. Therefore, the measure of preventing air intake in gate shaft is unwise and the pressure distribution of the tunnel body should be improved firstly. Some improving measures are adopted in the mode test, such as the inlet form optimizing and 15% area reduction of the outlet section. The inlet form optimizing improves the pressure distribution of the horn mouth and transition. The increased outlet top slope grade increases the pressure of the whole tunnel body. The result is that the phenomenon of air intake in gate shaft disappears, the whirlpool intensity is reduced upstream the inlet, the discharge section of alternation of free and pressure flow is narrowed obviously. However, the outlet top slope grade affects discharge capacity greatly. So the reduction value of the outlet top slope grade should be determined according to the design requirement of discharge capacity.

3.3 The choice and the optimization of inlet top form

There are two types of sharp-edged form and curving form for the inlet top of tunnel. As mentioned in 2.2.2, for steep slope tunnel, both inlet top forms can bring the conflict between discharge capacity and the internal flow pattern. The inlet top of sharp-edged form can prevent from alternation of free and pressure flow but result in lower discharge capacity. The curving inlet top of form can bring higher discharge capacity but result in alternation of free and pressure flow. So the balance must be achieved according to project cost and tunnel operation safety. On the premise that project cost increases not too much, the design of steep slope tunnel should adopt the inlet top of sharp-edged form to avoid alternation of free and pressure flow as possible.

3.4 Other measures

For steep slope tunnel, when $1.2 < H / a < k_{2s}$ and the tunnel length is short, the wise design of tunnel section dimension and tunnel length can result in $h_0 < a$ and prevent alternation of free and pressure flow. In the condition of the permitted terrain, geology and downstream energy dissipating arrangement, the tunnel length should be reduced as possible to make $l < l_{ks}$ and narrow the discharge section of alternation of free and pressure flow.

4. Conclusions and suggestions

(1) The hydraulic characteristics of steep slope tunnel are different from that of slight-grade tunnel. The alternation of free and pressure flow is easy to happen in the former. This kind of flow belongs to an unstable flow status which transforms between free flow and pressure flow and can bring cavitation damage, vibration damage and impact damage to the tunnel.
(2) The main influencing factors, which can result in alternation of free and pressure flow, include the relative submerged depth H/a at the inlet, tunnel form (bottom slope, inlet top form, tunnel height, tunnel length, curving section and gate shaft etc.), inlet guiding channel arrangement, resulted inhaling whirlpool and air intake in gate shaft etc.
(3) According to the terrain condition, geological condition, project function, operation safety and economic factor etc., some control measures such as whirlpool suppression, inlet form optimizing, wise choice of inlet top form and the outlet top slope, the optimization of tunnel height and length etc., can be adopted to improve the phenomenon of alternation of free and pressure flow in steep slope tunnels.
(4) For steep slope tunnel, aside from the complex internal flow pattern, there are some hydraulics problems such as the unmatured calculating method of discharge capacity, great negative pressure in the tunnel body, long negative pressure zone, great flow velocity and downstream energy dissipating etc., which also need to be researched in depth.

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