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Theoretical analysis on load of shallow tunnel under unsymmetrical pressure

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ABSTRACT: according to the investigation and study of the literature about the bias tunnel, this paper summarizes that the bias tunnel is mainly caused by the terrain, geological reasons and construction reasons; summarizes and analyzes the shallow buried tunnel and the bias tunnel, and puts forward the judgment standard of the shallow buried bias tunnel. This paper deduces the theoretical formula for calculating the surrounding rock load of shallow unsymmetrical tunnel, analyzes the surrounding rock load of caozigang tunnel, and solves the theoretical solution of the load of shallow unsymmetrical tunnel when the vertical pressure, lateral pressure, lateral pressure coefficient and fracture angle of surrounding rock change under different ground slope angle and different tunnel overburden thickness.

Key words: shallow buried / unsymmetrical tunnel / load / theoretical analysis

I. CAUSES AND DETERMINATION OF 1 SHALLOW TUNNEL UNDER UNSYMMETRICAL PRESSURE

1.1 causes of shallow bias tunnel formation

Unsymmetrical pressure tunnel refers to the tunnel in which the supporting structure bears a large unsymmetrical load due to the obvious asymmetry of surrounding rock pressure. The main factors that cause the bias load effect of tunnel are terrain, geology and construction. The first two factors belong to the internal factors in tunnel construction, and the third one belongs to the external factors.

1) Topographical causes

It mainly occurs in the entrance section of mountain side tunnel and shallow buried tunnel. The slope of the surface cross slope is generally steep. Under the action of asymmetric load, the unsymmetrical pressure occurs due to the unequal lateral pressure on both sides of the tunnel lining, as shown in Fig.1.

2) Geological causes

The main reason is that the attitude of surrounding rock strata is inclined, the rock joints are developed, and there are weak joint surfaces or sliding surfaces between different rock strata or structural planes. Once affected by the construction excavation disturbance, the relatively sTab. rock strata in the original rock state without external force will slide along the bedding plane, causing the bias of the tunnel, as shown in Fig. 2.

3) Construction reasons

Unreasonable excavation method or untimely construction of supporting structure lead to instability and collapse of surrounding rock on one side of the tunnel during excavation, change the stress distribution of surrounding rock pressure, cause stress concentration in the tunnel structure, and make the tunnel bear the effect of bias load, as shown in Fig.3.

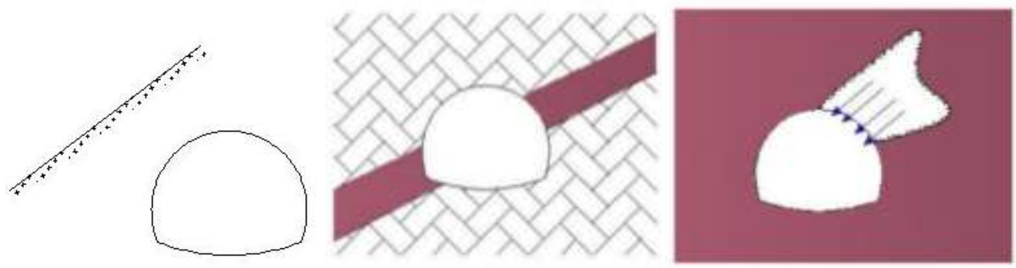

Fig.1 bias caused by topography Fig. bias caused by geology Fig. 3 bias caused by construction

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1.2 judgment of shallow bias tunnel

1) Judgment of shallow tunnel

For unsymmetrical pressure tunnel, the load of surrounding rock is related to the buried depth of tunnel. The distribution of surrounding rock pressure is different with different buried depth of tunnel, so the theory of calculating the load of surrounding rock is different. Therefore, it is necessary to determine the boundary between shallow and deep buried of tunnel.

The judgment of shallow and deep buried tunnel is mainly based on the equivalent height of the load, and needs to consider the geological conditions, construction conditions and other factors.

The formula determined by the equivalent height of load is as follows:

$$H_p = (2 \sim 2.5)\mathrm{h}_q$$
$$h_q = 0.45 \times 2^{s-1} \omega \qquad (1)$$
$$\omega = 1 + i(\mathrm{B} - 5)$$

Here： H_p ——Boundary depth between shallow and deep tunnels；

h_q ——Equivalent load height；

s ——Surrounding rock grade；

ω ——Width influence coefficient；

i ——Based on B = 5, the increase and decrease rate of surrounding rock pressure when B increases or decreases by 1 m，when B＜5m，i =0.2，when B＞5 时，i =0.1；

Under the condition of mining method excavation, HP = 2.5hq for grade IV ~ VI surrounding rock and HP = 2.0hq for grade I ~ III surrounding rockq。

2) Judgment of bias tunnel

The bias of tunnel is mainly determined by the grade of surrounding rock, ground slope, the ratio of the minimum overburden thickness at the outer spandrel of tunnel to the tunnel diameter (T / b). In the vertical direction, when the distance (T) between the outer spandrel of the tunnel and the ground surface is equal to or less than the value listed in Tab.1, the tunnel should be regarded as a bias tunnel, and the calculation of surrounding rock pressure should be considered as a bias tunnel.

Tab.1 vertical distance between outside spandrel and ground surface of bias tunnel (m)

Rock grade	Ground slope			
	1:1	1:1.5	1:2	1:2.5
Ⅳ$_{stone}$	5	4	4	——
Ⅳ$_{soil}$	10	8	6	5.5
Ⅴ	18	16	12	10

II. CALCULATION THEORY OF SURROUNDING ROCK LOAD OF SHALLOW TUNNEL UNDER UNSYMMETRICAL PRESSURE

2.1 determination of surrounding rock load

Due to the disturbance of tunnel excavation, the stress of surrounding rock is redistributed, and the deformation is loose and damaged. The pressure on the support or lining of tunnel mainly includes the stress of surrounding rock caused by in-situ stress and the force acting on the support structure due to the obstruction of surrounding rock deformation by the support structure.

2.2 calculation theory of single hole eccentric load

In the code for design of highway tunnels (JTGD70-2004), the theoretical calculation formulas of vertical pressure and horizontal lateral pressure of surrounding rock of single tunnel under eccentric pressure are given. The distribution of surrounding rock pressure of single tunnel under eccentric pressure is shown in Fig.4.

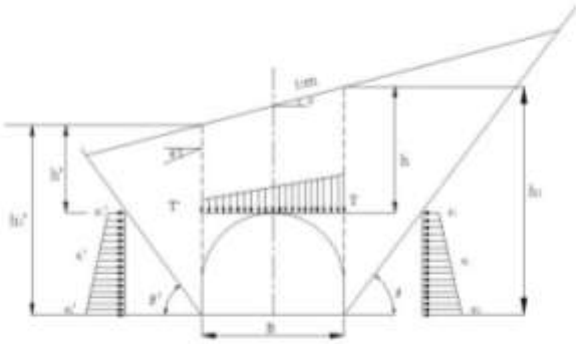

Fig.4 distribution of surrounding rock pressure of single tunnel under eccentric pressure by standard method

It is assumed that the surrounding rock pressure of the bias tunnel is distributed according to the terrain, as shown in the figure above.

$$Q=\frac{\gamma}{2}[(h_1+h_1^{'})B-(\lambda h_1^2+\lambda^{'} h_1^{'2})\tan\theta] \quad (2)$$

Here：Q——Total vertical pressure；

h_1、$h_1^{'}$——The height of the inner and outer sides from the vault level to the ground surface（m）；

B——Tunnel excavation width（m）；

γ——Weight of surrounding rock（KN/m^3）

θ——Friction angle on both sides of roof soil column（°）；

λ、$\lambda^{'}$——Lateral pressure coefficient of deep and shallow burial；

$$\lambda=\frac{1}{\tan\beta-\tan\alpha}\times\frac{\tan\beta-\tan\varphi_c}{1+\tan\beta(\tan\varphi_c-\tan\theta)+\tan\varphi_c\tan\theta} \quad (3)$$

$$\lambda^{'}=\frac{1}{\tan\beta^{'}+\tan\alpha}\times\frac{\tan\beta^{'}-\tan\varphi_c}{1+\tan\beta^{'}(\tan\varphi_c-\tan\theta)+\tan\varphi_c\tan\theta} \quad (4)$$

$$\tan\beta=\tan\varphi_c+\sqrt{\frac{(\tan^2\varphi_c+1)(\tan\varphi_c-\tan\alpha)}{\tan\varphi_c-\tan\theta}} \quad (5)$$

$$\tan\beta^{'}=\tan\varphi_c+\sqrt{\frac{(\tan^2\varphi_c+1)(\tan\varphi_c+\tan\alpha)}{\tan\varphi_c-\tan\theta}} \quad (6)$$

Here：α——Topographic bias angle（°）；

φ_c——Calculation of friction angle of surrounding rock（°）；

β——The fracture angle corresponding to the maximum thrust on the inner side of friction angle is calculated（°）；

$\beta^{'}$——The rupture angle corresponding to the maximum thrust on the outside（°）；

Calculation of vertical pressure and horizontal lateral pressure of single tunnel under eccentric pressure：

Vertical pressure：

$$q_0=Q/B \quad (7)$$

$$q_1=q_0-\frac{B\gamma}{2}\tan\alpha \quad (8)$$

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$$q_2 = q_0 + \frac{B\gamma}{2}\tan\alpha \quad (9)$$

lateral pressure：

Shallow buried side $e = \gamma h \lambda$ （10）

Deep buried side $e^{'} = \gamma h^{'} \lambda^{'}$ （11）

Here： q_1、 q_2 ——Vertical pressure on left and right sides of tunnel top；

h_i、 $h_i^{'}$ ——Distance from i to surface slope at any position inside and outside（m）。

The values of physical and mechanical parameters of surrounding rock at all levels are shown in Tab. 2, and the values of friction angle θ of soil column on both sides of roof are shown in Tab. 3.

Tab.2 physical and mechanical parameters of surrounding rocks at all levels

Rock grade	Density γ（KN/m^3）	Deformation modulus E(Gpa)	Poisson's ratio μ	internal friction angle φ （°）	Cohesionc（Mpa）	Calculation of friction angle φ_c （°）
Ⅰ	26~28	>33	<0.2	>60	>2.1	>78
Ⅱ	25~27	20~33	0.2~0.25	50~60	1.5~2.1	70~78
Ⅲ	23~25	6~20	0.25~0.3	39~50	0.7~1.5	60~70
Ⅳ	20~23	1.3~6	0.3~0.35	27~39	0.2~0.7	50~60
Ⅴ	17~20	1~2	0.35~0.45	20~27	0.05~0.2	40~50
Ⅵ	15~17	<1	0.4~0.45	<20	<0.2	30~40

Tab.3 values of friction angle θ of soil column of each rock grade

Rock grade	Ⅰ、Ⅱ、Ⅲ	Ⅳ	Ⅴ	Ⅵ
θ	0.9 φ_c	（0.7~0.9） φ_c	（0.5~0.7） φ_c	（0.3~0.5） φ_c

III. CASE STUDY ON SURROUNDING ROCK LOAD

The pile numbers of the left and right line entrance sections of Caozigang tunnel are zk10 + 335 and K10 + 224 respectively, and the longitudinal distance interval is 111m. The left tunnel belongs to single hole bias pressure at the entrance. The standard method is used for theoretical analysis, and the load model of single hole bias pressure tunnel is used for calculation to analyze the surrounding rock pressure load of caozigang tunnel. The tunnel excavation width is 10.75m, and the excavation height is 5.0m The selection of number is shown in Tab.4.

Tab. 4 values of tunnel surrounding rock parameters

Rock grade	slopeα（°）	Density γ（ KN/m^3 ）	internal friction angle φ （°）	Cohesion（GPa）	Calculation of friction angle φ_c （°）	Friction angle on both sides of roof soil column θ （°）
V	50	20	25	0.1	48	33.6

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3.1 analysis of surrounding rock pressure under the change of surface slope angle

According to the standard method, under the condition that the overburden thickness of the tunnel top is 6m, it changes with the slope gradient of the ground（15º、20º、25º 、30º、35º、40º、45º）, The calculation results of vertical pressure on the inner and outer sides of shallow bias tunnel top are shown in Tab. 5 and Fig.5. See Tab.6 and fig. 6 for the calculation results of horizontal pressure on the inner and outer sides.

Tab. 5 calculated values of vertical pressure at tunnel top under different slope conditions（KPa）

Bias angle（°）	q_1	q_0	q_2
15º	81.7	110.5	139.3
20º	71.2	110.3	149.4
25º	59.8	109.9	160.1
30º	47.4	109.5	171.6
35º	33.6	108.9	184.2
40º	17.8	108.1	198.2
45º	0	106.8	214.3

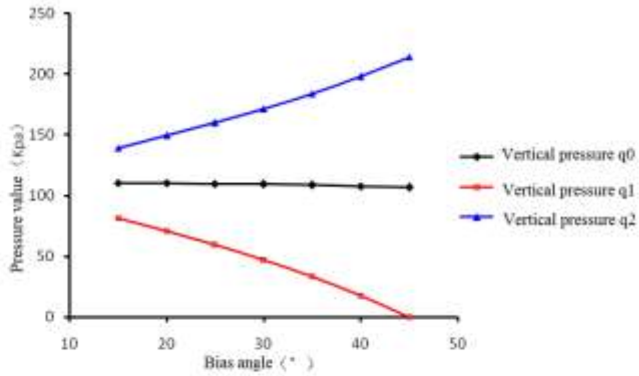

Fig.5 variation curve of vertical pressure at tunnel top with slope angle

Tab. 6 calculation values of horizontal pressure on both sides of tunnel under different slope conditions（KPa）

Slope angle（°）	λ'	e_1'	λ	e_1
15º	0.193	17.56	0.225	33.50
20º	0.188	15.21	0.233	37.10
25º	0.184	12.83	0.243	41.26
30º	0.179	10.38	0.255	46.33
35º	0.175	7.81	0.271	52.84
40º	0.170	5.06	0.295	61.92
45º	0.165	2.06	0.339	77.21

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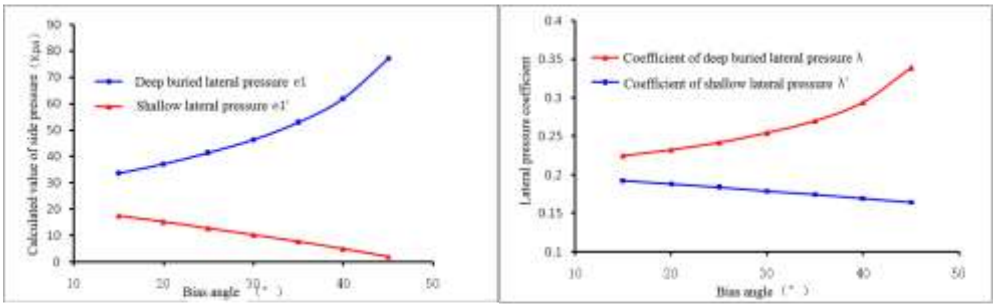

(a) Variation curve of lateral pressure (b) variation curve of lateral pressure coefficient
Fig. 6 variation curve of lateral pressure and coefficient of lateral pressure on both sides of tunnel with bias angle

From the calculation results and variation curve, it can be seen that:

(1) When the slope angle changes from 15 ° to 20 °, 30 ° and 40 ° gradually, the average vertical pressure q0 on the top of the tunnel changes little, but the difference between the two sides of the shallow bias tunnel gradually increases; at 15 ° the average difference is 57.6kpa, at 20 ° the average difference is 78.2kpa, at 30 ° the average difference ∇q is 124.2kpa, at 40 ° the average difference is 180.4kpa. It can be seen that the vertical pressure of tunnel surrounding rock is affected by eccentric pressure, and the larger the slope angle is, the greater the vertical pressure shared by the deep buried side is, and the smaller the vertical pressure shared by the shallow buried side is.

(2) The vertical pressure distribution of tunnel cross section is affected by the slope angle. With the increase of the slope angle, the vertical pressure value of deep buried side is larger and larger, while the vertical pressure value of shallow buried side is smaller and smaller, which is significantly affected by the slope angle.

(3) With the increase of the slope angle, the lateral pressure coefficient $\lambda^{'}$ of the deep buried side of the tunnel gradually decreases, and the lateral pressure coefficient of the shallow buried side gradually increases. It shows that with the increase of slope angle, the effect of topographic bias on the deep buried side is obviously enhanced, while that on the shallow buried side is gradually weakened.

(4) When the slope angle changes from 150 to 200, 300 and 450, the lateral pressure on the shallow side of the tunnel decreases from 17.56kpa to 2.06kpa, while the lateral pressure on the deep side of the tunnel increases from 33.50kpa to 77.21kpa. It shows that with the increase of slope angle, the lateral pressure shared by deep buried side increases gradually, while the lateral pressure shared by shallow buried side decreases gradually.

3.2 analysis of surrounding rock pressure under variation of overburden thickness of tunnel

According to the calculation results of the vertical pressure on the inside and outside of the tunnel top under different buried depths when the grade V surrounding rock and the ground slope angle are 30 ° are shown in Tab.7 and Fig.7. See Tab.8 and fig.8 for the calculation results of horizontal pressure inside and outside the tunnel.

Tab.7 calculation values of vertical pressure at tunnel top under different buried depth conditions（KPa）

Tunnel depth（m）	q1	q0	q2
6	47.44	109.51	171.57
8	80.51	142.58	204.64
10	111.44	173.50	235.57
15	179.38	241.44	303.51
20	233.92	295.98	358.05
25	275.05	337.12	399.18
30	302.79	364.85	426.92

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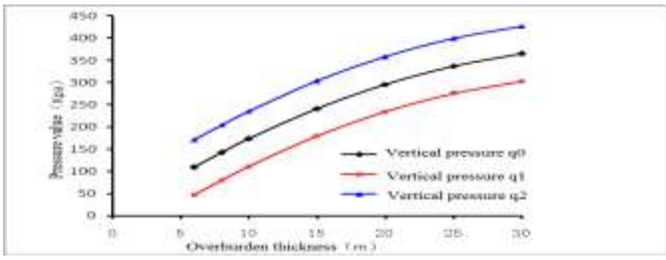
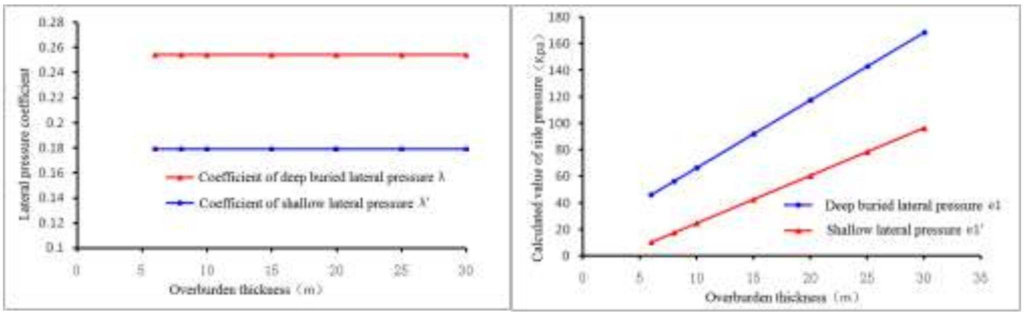


Fig. 7 variation curve of vertical pressure at tunnel top with overburden thickness

Tab.8 calculation values of horizontal pressure on both sides of tunnel under different buried depth conditions (KPa)

Tunnel depth (m)	λ'	e_1'	λ	e_1
6	0.179	10.38	0.254	46.33
8	0.179	17.55	0.254	56.51
10	0.179	24.72	0.254	66.69
15	0.179	42.64	0.254	92.14
20	0.179	60.55	0.254	117.59
25	0.179	78.47	0.254	143.04
30	0.179	96.39	0.254	168.49



(a) Variation curve of lateral pressure coefficient (b) variation curve of lateral pressure
Fig. 8 variation curve of lateral pressure and coefficient of lateral pressure on both sides of tunnel with thickness of overburden

From the calculation results and variation curve, it can be seen that:
(1) The vertical pressure on the top of tunnel increases with the increase of buried depth, but when the buried depth exceeds 25m, the increasing rate decreases obviously.
(2) The lateral pressure on both sides of the tunnel increases with the increase of the buried depth, but when the buried depth is more than 25m, the ratio of the deep buried lateral pressure to the shallow buried lateral pressure is obviously smaller, that is, when the buried depth is more than 25m, the bias effect of the tunnel is weakened, and the bias effect is obviously reduced, which can be designed without considering the bias characteristics of the tunnel.
(3) According to the calculation formula of lateral pressure coefficient, the value of lateral pressure coefficient has nothing to do with the buried depth, but only with the toe of the ground slope and the lithology of surrounding rock and its parameters. The calculation curve also verifies this point, and the lateral pressure coefficient remains unchanged with the change of tunnel buried depth.

3.3 analysis of fracture angle on both sides of tunnel

When the thickness of class V surrounding rock and overburden is 6m, the calculation results of the fracture angle values of the deep and shallow buried sides of the tunnel under different slope angles are shown in Tab. 9 and Fig.9, and the schematic diagram of the failure mode of the tunnel is shown in Fig.10. When the ground slope angle is 30 ° and the overburden thickness is different, the calculation results of the fracture angle at the deep and shallow buried sides of the tunnel are shown in Tab. 10 and

Fig.11.

Tab. 9 calculated values of rupture angle under different ground slope angles

Bias angle (°)	Fracture angle of deep buried sideβ (°)	Shallow side rupture angleβ' (°)
15°	72.46	75.02
20°	71.81	75.36
25°	71.01	75.69
30°	69.98	76.02
35°	68.54	76.36
40°	66.28	76.71
45°	61.67	77.08

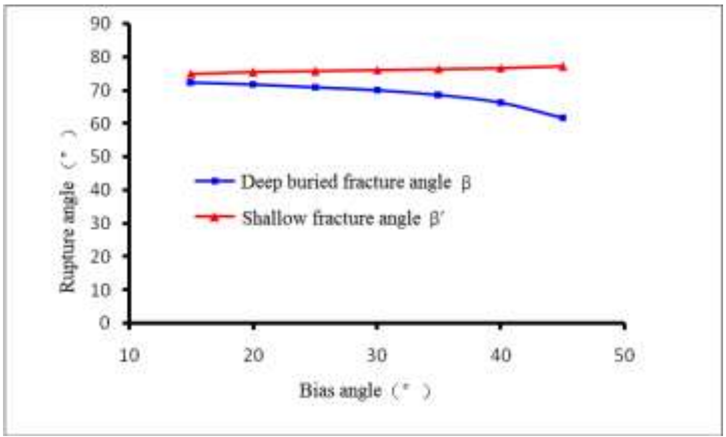


Fig. 9 variation of rupture angle with slope angle

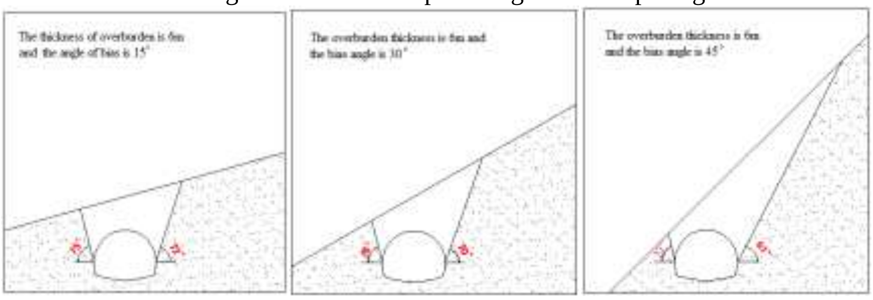


Fig. 10 schematic diagram of failure modes of tunnels with different ground slope angles

Tab.10 calculation value of fracture angle under different buried depth

Buried depth (m)	Fracture angle of deep buried sideβ (°)	Shallow side rupture angleβ' (°)
6	69.98	76.02
8	69.98	76.02
10	69.98	76.02
15	69.98	76.02
20	69.98	76.02
25	69.98	76.02
30	69.98	76.02

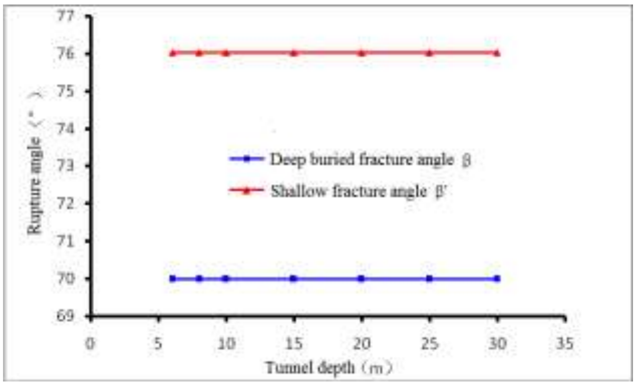


Fig. 11 variation curve of fracture angle with tunnel depth

From the calculation results and variation curve, it can be seen that:

(1) The fracture angle is affected by the ground slope angle of the tunnel. The change law of the fracture angle in the deep buried side of the tunnel decreases with the increase of the slope angle. When the slope angle exceeds 350, the change rate of the fracture angle increases. The change law of the fracture angle in the shallow buried side slightly increases with the increase of the slope angle, and the influence is small. That is to say, the larger the slope angle of the tunnel, the larger the failure area of the rock and soil mass at the deep buried side, while the failure area of the rock and soil mass at the shallow buried side remains basically unchanged.

(2) According to the calculation formula of fracture angle, the size of fracture angle has nothing to do with the buried depth of the tunnel, but only with the slope angle of the ground and the lithology and parameters of the surrounding rock. The calculation curve also verifies that the size of fracture angle remains unchanged with the change of the buried depth of the tunnel.

IV. CONCLUSION

(1) With the increase of ground slope angle, the vertical pressure value of deep buried side is larger and larger, while the vertical pressure value of shallow buried side is smaller and smaller; the lateral pressure coefficient λ' of shallow buried side of tunnel gradually decreases, and the lateral pressure coefficient λ of deep buried side gradually increases. It shows that with the increase of slope angle, the effect of bias on deep buried side is obviously intensified, while the effect of bias on shallow buried side is gradually reduced; the size of fracture angle on deep buried side decreases with the increase of bias angle, and the size of fracture angle on shallow buried side slightly increases with the increase of bias angle, which has less influence, that is, the larger the slope angle of tunnel is, the larger the damage area of rock and soil on deep buried side is However, the failure area of rock and soil mass near the shallow buried side remains unchanged.

(2) With the increase of the tunnel depth, the vertical pressure on the top of the tunnel becomes larger and larger, but when the depth is greater than 25m, the increase rate decreases obviously; the lateral pressure on both sides of the tunnel increases with the increase of the depth, but when the depth is greater than 25m, the ratio of the lateral pressure on the deep side to the lateral pressure on the shallow side is significantly smaller, that is, when the depth is greater than 25m, the lateral pressure on both sides of the tunnel increases The results show that the effect of bias decreases with the decrease of bias, and the fracture angle has nothing to do with the tunnel depth, but remains unchanged with the change of tunnel depth.

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