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Reliability Index Analysis on Anchor-Shotcret Support of Tunnel under Non-Symmetrical Condition

[1]Ding Jihui, [1]Yuan Man, [2]Z Hang Chunbao and [2]Xi Yinghua
[1]College of Civil Engineering, Hebei University, Baoding 071002, China
[2]Baoding City Zhang-Zhuo Expressway Management Preparation Office,Baoding 071051, China

Abstract: In this study, we build the analytical models of reliability index on anchor-shotcret support structure of tunnel which is non-symmetrica. Considered function's high non-linear, the reliability index computation is adopted by Monte-Carlo method. The calculation results show that reliability index decreases when variation coefficients of crustal stress, cohesive force, inner friction angle, thickness of shotcrete layer, concrete compression strength and extension strength of anchor-shotcret and anchoring force increased and reliability index increases when variation coefficients of tunnel radius and final origin angle of broken wedge increases. Variation coefficients of inner friction angle, tunnel radius and final origin angle of broken wedge has outstanding influence on reliability index and then thickness of shotcrete layer, concrete compression strength, cohesive force, crustal stress and anchoring force. Reliability index increases with lateral pressure factor increased. Reliability index rapid decreases with crustal stress increased.

Keywords: Anchor-shotcret support, elastic-plasticity theory, monte-carlo method, non-symmetry, reliability index

INTRODUCTION

The anchor-shotcret support structure design of the tunnel is adopted engineering analogy or experience judgment method, it is unreasonable that safety index of structure is measured by safety factor. The multiple-failure model or stabile state of anchor-shotcret support system are considered and the optimization design of tunnel engineering are made by using failure probability or safety probability to evaluate the stability of tunnel surrounding rocks or failure risk. There are Rosenblueth Point Estimation (Rosenblueth, 1975, 1981; Yong-hua *et al*., 2004), JC method, Monte-Carlo method, Response Surface Method (Xi-an, 2011; Yong-hua *et al*., 2000; Wang, 1993), optimization method (geometric method) (Lu and Wu, 1988) and probability FEM method (Liu, 2001) on calculation methods of reliability index. Based on the anchor-shotcret support structure of tunnel, the analytical models of reliability index under non-symmetrical condition are built. and the affect factors are analyzed by Monte-Carlo method (Rajashekhar and Ellingwood, 1993).

In this study, the analytical models of reliability index on anchor-shotcret support structure of tunnel which is non-symmetrical are built. Considered function's high non-linear, the reliability index computation is adopted by Monte-Carlo method. The effect factors are discussed thought the engineering example and the calculation results show that variation coefficients of inner friction angle, tunnel radius and final origin angle of broken wedge has outstanding influence on reliability index and then thickness of shotcrete layer, concrete compression strength, cohesive force, crustal stress and anchoring force.

METHODOLOGY

The limit state equations' construction: Under non-symmetrical condition, when lateral pressure factor $\lambda<8$, Robcewitc considered that shear failure occurs both sides of the concrete spraying layer, slide line equation is replaced by the equation with symmetrical condition(λ=1). That is (Xu and Bai, 2002):

$$l_{max} = r_0\{\exp[(\pi/2-\rho)\cot \beta_1-1]-1\} \tag{1}$$

where, β_1 is the included angle of between the tangent of slide line and coordinate axle direction; r_0 is the tunnel radius; ρ is final origin angle of broken wedge; l is the maximum length of broken wedge.

Suggestion value of λ: if λ = 0.2~0.5, then ρ = 50~40°; if λ= 0.5~0.8, then ρ = 40~35.

The limit state equations of concrete spraying retaining and rrotecting:

To ensure spraying retaining does not occur shear failure, resist force of retaining and protecting is (Xu and Bai, 2002):

$$p_i = -c\cot\varphi + (\sigma_z + c\cot\varphi)(1-Sin\varphi)\left(\frac{r_0}{R}\right)^{\frac{2Sin\varphi}{1-Sin\varphi}} \tag{2}$$

Corresponding Author: Ding Jihui, College of Civil Engineering, Hebei University, Baoding 071002, China

$$R = r_0 \exp\{(\theta - \rho)\cot(45^o + \varphi/2)\} \quad (3)$$

where, p_i is the minimum resist force ensuring stability of tunnel surrounding rocks; σ_z is the crustal stress in vertical direction; c and ϕ are respectively cohesive force and inner friction angle of tunnel surrounding rocks.

The condition to ensure spraying retaining does not occur shear failure is (Xu and Bai, 2002):

$$K_4 p_i r_0 \cos\rho = \frac{\tau_c t}{Sin(45^o - \varphi/2)} \quad (4)$$

where, τ_c is resisting shear strength of concrete spraying layer, generally τ_c=0.2R_h; R_h is resisting compression strength of concrete; t is the thickness of spraying layer. The limit state equation spraying layer is:

z_1=τ_ct−sin(45°−φ/2)r_0 cos ρ•

$$\left\{(\sigma_z + c\cot\varphi)(1 - \sin\varphi)\left(\frac{r_0}{R}\right)^{\frac{2\sin\varphi}{1-\sin\varphi}} - c\cot\varphi\right\} = 0 \quad (5)$$

The condition to ensure retaining does not occur compression and shear failure acted p_i is (Xu and Bai, 2002):

$$K_3 = \frac{t}{r_0\left\{1/\sqrt{1 - 2p_i/R_h - 1}\right\}} \quad (6)$$

The limit state equation of spraying layer is:

$$z_2 = t - r_0\left\{1/\sqrt{1 - 2p_{i3}/R_h} - 1\right\} = 0 \quad (7)$$

The failure probability of spraying layer is:

p_f = max{P(z_1 <0), P(z_2<0)}
β_f = min{β_1, β_2}

The limit state equations of anchor-shotcret support: The anchors are used to improve the cohesive force and inner friction angle of tunnel surrounding rocks.
There is:

$$\varphi_1 = \varphi,\ c_1 + \tau_a A_5/ab \quad (8)$$

where, c_1, φ_1 are respectively cohesive force and inner friction angle of improved tunnel surrounding rocks; τ_a is the shear strength of anchor-shotcret; a and b are respectively longitudinal and transverse space; A_s is the cross section of a single anchor.

To ensure spraying retaining does not occur shear failure, resist force of retaining and protecting is (Xu and Bai, 2002):

$$p_i + p_a = -c_1\cot\varphi_1 + (\sigma_z + c_1\cot\varphi_1)(1 - Sin\varphi_1)\left(\frac{r_0}{R}\right)^{\frac{2Sin\varphi_1}{1-Sin\varphi_1}} \quad (9)$$

where, p_a is the additional resist force by anchor.
p_a is determined as follows:

$$p_a = A_s f_{st}/ab \quad (10)$$

where, f_{st} extension strength of anchor-shotcret.
The anchoring force also satisfies:

$$p_a = F/ab \quad (11)$$

The function of shotcrete layer and anchoring is:
z_1=τ_ct−sin(45°−φ/2)r_0 cos ρ•

$$\left\{(\sigma_z + c_1\cot\varphi_1)(1 - \sin\varphi_1)\left(\frac{r_0}{R}\right)^{\frac{2\sin\varphi_1}{1-\sin\varphi_1}} - c_1\cot\varphi_1 - \frac{A_s f_{st}}{ab}\right\} \quad (12)$$

The function of shorcrete layer and anchor is:
z_2 = τ_ct-sin(45°−ϕ/2)r_0 cos ρ•

$$\left\{(\sigma_z + c_1\cot\varphi_1)(1 - \sin\varphi_1)\left(\frac{r_0}{R}\right)^{\frac{2\sin\varphi_1}{1-\sin\varphi_1}} - c_1\cot\varphi_1 - \frac{F}{ab}\right\} \quad (13)$$

The failure probability of sotcrete layer and anchor is:

P_f = max{P(z_1<0), P(z_2<0)}
β_f = min {β_1, β_2}

ENGINEERING EXAMPLE

Considered function's high non-linear, the reliability index computation is adopted by Monte-Carlo method (Ding and Liang, 2010).

Some deep buried tunnel, λ = 0.5. Anchor length l = 1.5 m, anchor diameter d = 1.4 cm, a = 0.75 m, b = 0.75 m, concrete irons is rank I. The statistical parameters as shown in Table 1. Assumes that all statistical variables obey normal distribution and variation coefficients are equal to 0.1.

Without anchor, let K_4 = 1.5, τ_c = 0.2R_c, the parameters as shown in Table 1 are substituted formula (4), there is t = 13.2 cm.

Table 1: The statistical parameters of anchor-shotcret support structure

Variables	Variables	Mean value
σ_z/MPa	X_1	7.50
c / MPa	X_2	0.30
φ/°	X_3	40.00
r_0/m	X_4	2.00
t / m	X_5	0.14
ρ /°	X_6	40.00
R_c/ MPa	X_7	11.00
f_{st}/ MPa	X_8	380.00
F / kN	X_9	60.00

Table 2: Computation results

Failure model	S	β	p_f
Without anchor	shear failure	0.692	0.244415
	compression and shear failure	1.562	0.059105
With anchor	shotcret layer+ anchor yield	1.283	0.097950
	shotcret layer +anchorage	1.291	0.098375

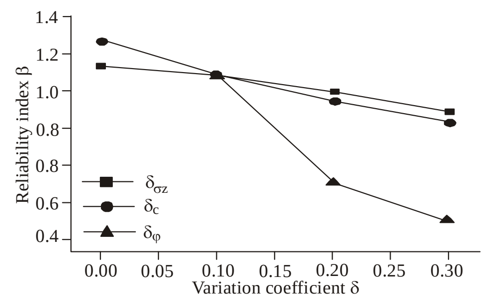

Fig. 1: $\beta \sim (\delta_c, \delta_\phi)$ curve

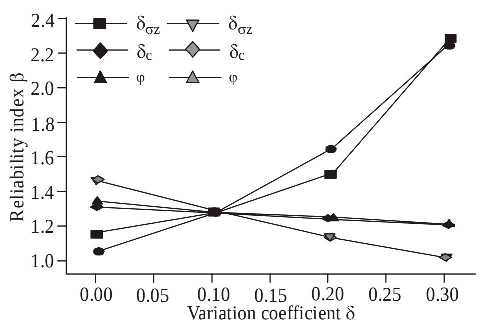

Fig. 2: : $\beta \sim \delta_\rho(\delta_t, \delta_{Rc}\ \delta_{fst}, \delta_F)$ curve

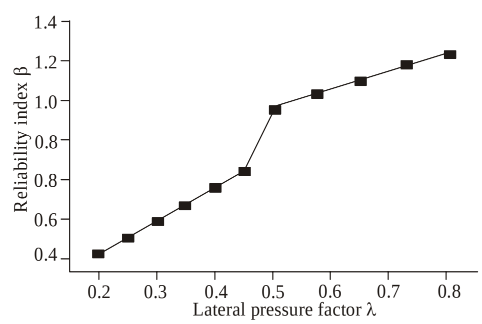

Fig. 3: $\beta \sim \lambda$ relation curve

Let $K_3 = 1.2$, the parameters as shown in Table 1 are substituted formula (6), there is t = 6.8 cm.

Therefore, the thickness of concrete praying layer is 14 cm.

The computation results are adopted by Monte-Carlo method as show in Table 2 and Fig. 1to 4.

With no anchor, the failure probability of spraying layer:

$$p_f = \max(p_{f1}, p_{f2}) = 0.2444150$$
$$\beta_f = \min\{\beta_1, \beta_2\} = 0.6922$$

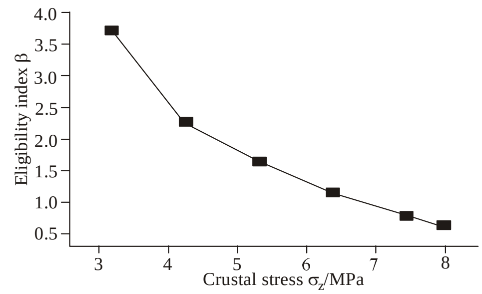

Fig. 4: $\beta \sim \sigma_z$relation curve

With anchor, the failure probability of spraying layer and anchor:

$$p_f = \max(p_{f1}, p_{f2}) = 0.0997945$$
$$\beta_f = \min\{\beta_1, \beta_2\} = 1.282720$$

As shown in Fig. 1 and 2, at λ=0.5, the calculation results show that reliability index decreases when variation coefficients of crustal stress, cohesive force, inner friction angle, thickness of shotcrete layer, concrete compression strength and extension strength of anchor-shotcret and anchoring force increased and reliability index increases when variation coefficients of tunnel radius and final origin angle of broken wedge increases. When other parameters is constant, one of the variation coefficient is changed from 0.0 to 0.3, the reliability indexes of crustal stress, cohesive force, thickness of shotcrete layer, concrete compression strength and extension strength of anchor-shotcret and anchoring force, reliability indexes decreases respectively 19.4, 30.2, 32.0, 32.0, 8.9 and 9.8%; the variation coefficients of inner friction angle increases from 0.05 to 0.3, reliability indexes decreases 79.2%; the variation coefficients of tunnel radius and final origin angle of broken wedge increases from 0.0 to 0.3, reliability indexes increases 105.2 and 122.5%.

When other parameters are taken from Table 1 and all variation coefficients are equal to 0.1, Fig. 3 is the relation curve of reliability index with lateral pressure factor. Figure 4 shows that reliability index increases when lateral pressure factor increases. While λ = 0.2~0.8 reliability index β = 0.5920 ~1.5394.

As shown in Fig. 4, reliability index rapid decreases with crustal stress increased. When σ_z = 3.0~7.5 MPa and all variation coefficients are equal to 0.1, reliability index β = 3.706673~1.2688.

CONCLUSION

- Based on analytical solution of elasticity and plasticity theory of the circular tunnel surrounding rocks, the analytical models of reliability index on anchor-shotcret support structure of tunnel which is non-symmetrical are built. Considered function's high non-linear, the reliability index computation is adopted by Monte-Carlo method.

- The effect factors are discussed thought the engineering example and the calculation results show that variation coefficients of inner friction angle, tunnel radius and final origin angle of broken wedge has outstanding influence on reliability index and then thickness of shotcrete layer, concrete compression strength, cohesive force, crustal stress and anchoring force.
- Reliability index first increases and then decreases with lateral pressure factor increased, variation range of reliability index is small when lateral pressure factor is 0.5~0.8. Reliability index rapid decreases with crustal stress increased.

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