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The Reliability Calculation Method and Program Realization for the Railway Tunnel Portal Structure

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Abstract: Based on the traditional strip method, the five limit state performance functions of railway tunnel portal structure including compression, tensile, anti-overturning, anti-sliding and bearing capacity of foundation have been built in this paper. Then the partial factors and adjustment coefficients for each performance function have been determined through the target reliability index obtained from the calibration for railway tunnel general reference map and the design verification. In general, the calculation of the limit state of the tunnel portal structure and the reliability index are calculated by combining hand computation with MATLAB, ANSYS and EXCEL. This method has the disadvantages of low efficiency and poor practicability. So the software for calculating the tunnel portal structure based on the theory of limit state method has been developed by using Visual Basic, which has realized the function of calculating the reliability index and limit state of portal rapidly. Besides, the software has offered three methods to calculate the reliability index including JC method, quantile method and Monte-Carlo method. Moreover, the calculation results can be written to the EXCEL template file, which greatly improves the efficiency of calculating the tunnel portal structure. The accuracy of the software has been verified by comparing with the results of manual calculation.

Keywords: limit sate method, tunnel portal, reliability index, Visual Basic.

1 Introduction

As a kind of retaining structure, the main function of the tunnel portal is to stop the soil sliding from the slope to ensure the stability of the soil mass. Therefore it's ineluctable for the portal to bear the active soil pressure from the slope and it's necessary to check the bearing capacity and stability of the portal. At present, the allowable stress method and the limit state method are the main design methods of portal structure. The allowable stress method, which is mainly based on the engineering experience, is the standard design method adopted by the current code for design of railway tunnel in China (National Railway Administration of the People's Republic of China, 2017), but the limit state method that's based on the probability theory is an international general method adopted by America, Canada, Germany, Sweden, Japan and so on. However, there are few studies on reliability index and partial factor of mountain tunnel abroad, and in view of the different requirement for reliability of engineering structures in China, the foreign researches are for reference only.

Since the 90s of last century, the former Ministry of Railways carried out the basic research work on the transition of design standards of railway tunnels (Zhou et al. 2001, Li and Gao 2002, Yan et al. 2003, Zhao et al. 2015, Yu and Zhou 2015, Zhao and Feng 2016). However, the

studies are incomplete and not profound, which leads to the situation that the research results are only applicable to some specific working conditions. Therefore, in order to promote the application of limit state method and extend the sphere of application of limit state method, the target reliability indexes and limit state equations of different limit states for portal are determined based on the reliability theory in this paper. Then the partial factors of limit state expressions are optimized according to the target reliability indexes. Finally, in consideration of the complex process and the low efficiency for the reliability index calculation and limit state design through traditional method which combines hand computation with Matlab, Ansys and Excel, the software named Tunnel Reliability Analysis Software (TRAS) based on the Visual Basic is developed which realizes the functions of calculating the reliability index and limit state design of portal rapidly.

2 Target Reliability Index of Portal Structure

In general, the factors that affect the function requirements of structures can be summed up as two comprehensive quantities which are action effect S and resistance effect R respectively. The reliability state of structure can be expressed by performance function:

$$Z = g(R,S) = R - S \tag{1}$$

The portal structure just bears the gravity and soil pressure, so the performance functions of portal can be obtained easily which are listed in Table 1 according to Eq. (1).

Table 1. Performance functions

Limit states	Performance functions
Anti-cracking	$z_1 = \min\left\{\sigma_l - \left(-G/A \pm G\bullet d_p/W \mp E\bullet d_e/W\right)\right\}$
Anti-compression	$z_2 = \min\left\{\sigma_y - \left(G/A \pm G\bullet d_p/W \mp E\bullet d_e/W\right)\right\}$
Anti-overturning	$z_3 = Gd_p^{''} - E\bullet d_e^{'}$
Anti-sliding	$z_4 = G\bullet\mu - E$
Bearing capacity of foundation	$\lvert e\rvert \le B/6, z_5 = \min\left\{f_p - G/B^2 b\bullet(B \mp 6d_p^{'}) \pm 6E\bullet d_e^{'}/\left(B^2 b\right)\right\}$
	$\lvert e\rvert > B/6, z_5 = f_p - 4G/\left[3\left(B-2e\right)b\right]$

In the table, σ_l and σ_y are the ultimate tensile strength and ultimate compressive strength of portal respectively, W is the bending stiffness of portal trip, f_p is the ultimate compressive strength of foundation, G and E are the gravity of portal trip and soil pressure respectively, B and b are the width of the foundation and portal trip respectively, d_p and d_e are the distance from the action line of gravity and soil pressure to the centroid of checking section of trip respectively, $d_p^{'}$ and $d_e^{'}$ are the distance from the action line of gravity and soil pressure to the centroid of base respectively, $d_p^{''}$ is the distance from the action line of gravity to the toe of the portal , e is the base eccentricity. The soil pressure can be calculated using Eq. (2).

$$E = \gamma_s \lambda b\left[H^2 + h_0(h^{'} - h_0)\right]\xi/2 \tag{2}$$

where γ_s is the unit weight of soil, b is the calculation width of portal strip, ξ is the uncertainty coefficient and equals 0.45, λ is the lateral pressure coefficient , H, h0 and h' are as shown in Fig. 1.

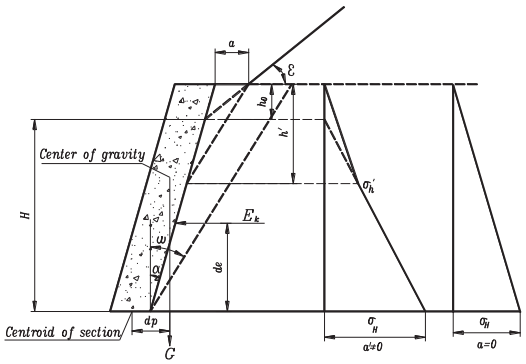

Figure 1. Distribution of soil pressure

The target reliability indexes of the portal structure are obtained through calibrating the reliability index of general reference map adopting JC method based on the performance functions listed in Table 1, which means the target reliability indexes inherit the reliability level of the original design code. The target reliability indexes also refer to similar industry standards of China and other countries. The final target reliability indexes are listed in Table 2.

Table 2. The target reliability indexes of railway tunnel portal

Safety level / Limit states	Level 1	Level 2	Level 3
Anti-cracking	5.2	4.7	3.7
Anti-compression			
Anti-overturning	2.5	2.0	1.5
Anti-sliding	2.5	2.0	1.5
Bear capacity of foundation	3.7	3.2	2.7

3 Limit State Expressions and Partial Factors of Portal Structure

3.1 *Limit state expressions*

According to the unified design standard for reliability of railway engineering structures, the following equation can be used for the limit state design of bearing capacity of structure.

$$\gamma_0 S_d(*) \le R_d(*) / \gamma_{Rd} \tag{3}$$

Where γ_0 is the importance factor of structure, γ_{Rd} is the uncertain partial coefficient of action calculation model, $S_d(*)$ is the design function of action effect and $R_d(*)$ is the design function of resistance effect. Based on Eq. (3), the limit state expressions of portal can be expressed as shown in Table 3.

In Table 3, G_{k1} and G_{k2} are the standard value of gravity and soil pressure respectively, f_t is the design value of concrete axial tensile strength which can be calculated with equation $f_t=f_{tk}/\gamma_{Rt}$ where f_{tk} is standard value of concrete axial tensile strength and γ_{Rt} is the partial factor of concrete axial tensile strength, f_c is the design value of concrete axial compressive strength which can be calculated with equation $f_t=f_{ck}/\gamma_{Rc}$ where f_{ck} is standard value of concrete axial compressive strength and γ_{Rc} is the partial factor of concrete axial compressive strength, f_p is the design value of controlled compressive stress of basement which can be calculated with equation $f_p=f_{pk}/\gamma_p$, f_m is the design value of foundation friction which can be calculated with equation

$f_m=f_{mk}/\gamma_f$ where f_{mk} is the standard value of foundation friction that can be computed with $f_{mk}=\gamma_{G1}\mu$ where μ is the friction coefficient and γ_f is the partial factor of foundation friction, γ_q is the partial factor of anti-overturning.

Table 3. Limit state expressions of portal structure

Limit states	Expressions
Anti-cracking	$\max\left\{-\left[\gamma_{G1}G_{k1}\left(t\pm 6d_p\right)/\left(bt^2\right)\mp\gamma_{G2}G_{k2}\cdot 6d_e/\left(bt^2\right)\right]\right\}\gamma_0\le f_t/\gamma_d$
Anti-compression	$\max\left[\gamma_{G1}G_{k1}\left(t\pm 6d_p\right)/\left(bt^2\right)\mp\gamma_{G2}G_{k2}\cdot 6d_e/\left(bt^2\right)\right]\gamma_0\le f_c/\gamma_d$
Anti-overturning	$\gamma_0\gamma_d\gamma_{G2}G_{k2}d_e^{'}\le\gamma_{G1}G_{k1}d_p^{''}/\gamma_q$
Anti-sliding	$\gamma_0\gamma_d\gamma_{G2}G_{k2}\le f_m$
Bearing capacity of foundation	$\lvert e\rvert\le B/6,\max\left[\gamma_{G1}G_{k1}\left(B\pm 6d_p^{'}\right)/\left(B^2b\right)\mp\gamma_{G2}G_{k2}6d_e^{'}/\left(B^2b\right)\right]\gamma_0\gamma_d\le f_p$
	$\lvert e\rvert>B/6,4\gamma_{G1}G_{k1}/\left[3\left(B-2e\right)b\right]\gamma_0\gamma_d\le f_p$

3.2 *Partial Factors*

After determining the target reliability indexes and building the limit state equations, the partial factors can be obtained. In order to keep unity with the code for design of concrete structures, the value of γ_{Rt} and γ_{Rc} are taken as 1.4, and the coefficient of uncertainty of soil pressure ξ=0.45 is incorporated into the partial factor of the soil pressure γ_{G2} which is taken as 1.4. Firstly, the partial coefficients are solved by the quantile method, and then the partial coefficients are calibrated and optimized according to the target reliability index listed in Table 2, finally the partial factors are readjusted through design verification. The final partial factors in Table 3 are as shown in Table 4.

Table 4. Partial factors of tunnel portal

Limit state / Partial factors	Crack resistance	Compression resistance	Bearing capacity of foundation	Anti-overturning	Anti-sliding
γ_{G2}	1.4	1.4	1.0	1.4	1.4
γ_{Rt}	1.4	-	-	-	-
γ_{Rc}	-	1.4	-	-	-
γ_p	-	-	1.15	-	-
γ_q	-	-	-	1	-
γ_f	-	-	-	-	1.75
γ_d	1.4	1.4	1.2	1.15	0.55

4 The Design of TRAS

4.1 *Function introduction*

The above sections introduced the determination method of target reliability index, and established the limit state expressions of tunnel portal structure. However, the traditional calculation approach that combines the hand calculation with some common software like Excel, Ansys, Matlab and so on has low computational efficiency in practical calculation. In view of that, the software named Tunnel Reliability Analysis Software (TRAS) is developed in the paper, which can realize the functions of reliability index calculation and the design of tunnel portal based on limit state method.

The software can solve the reliability index of portal structure by JC method, quantile method and Monte-Carlo method. The main processes consist of three steps: geometric parameter input, random parameter input and calculation, just as shown in Fig. 2~Fig. 4. The calculation results can be written into Excel file.

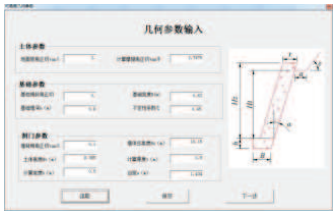

Figure 2. Geometric parameters

Figure 3. Random parameters

Figure 4. Results of JC method

Besides calculating the reliability indexes, the software can also realize the structure design based on limit state method. The main processes of the design include the input of geometric parameters, the input of coefficients and calculation, just as shown in Fig. 5~Fig. 7. The calculation results can also be inputted into Excel files automatically.

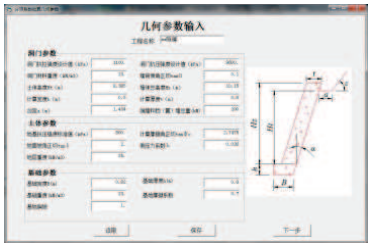

Fig4. Geometric parameters

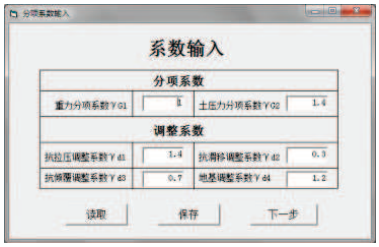

Fig 5. Input of coefficients

Fig 6. Calculation results

4.2 *Verification of calculation result*

In order to validate the accuracy of the software for calculating the reliability index and checking results of design, this section compares the results of software with that of traditional approach. The comparison results are as shown in Table 5 and Table 6.

Table 5 . Comparison results of reliability index

Methods / Calculation items	JC method		Quantile method		Monte Carlo method	
	TRAS	Tradition	TRAS	Tradition	TRAS	Tradition
Crack resistance	4.7	4.72	4.79	4.78	4.75	4.79
Compression resistance	5.25	5.24	5.25	5.25	$+\infty$	$+\infty$
Anti-overturning	3.74	3.74	3.74	3.74	3.7	3.73
Anti-sliding	4.47	4.47	4.5	4.5	4.38	4.42
Bearing capacity of foundation	3.52	3.51	3.52	3.53	3.6	3.58

As shown in Table 5 and Table 6, the results of software and traditional approach are basically consistent. The maximum difference of reliability index between the two approaches is only 0.04 and the value of action effect and resistance effect calculated by the software are

almost the same with the traditional approach. Therefore the TRAS has a high precision in calculating the reliability index and structure design based on limit state method.

Table 6. Comparison results of design verification of limit state method

Methods / Calculation items	Action effect		Resistance effect		Checking results	
	TRAS	Tradition	TRAS	Tradition	TRAS	Tradition
Crack resistance(kPa)	-185.11	-185.08	785.71	785.7	Pass	Pass
Compression resistance(kPa)	281.79	281.82	6857.14	6857.1	Pass	Pass
Anti-overturning(kN • m)	47.36	47.38	115.22	115.22	Pass	Pass
Anti-sliding(kN)	14.12	14.12	100.74	103.7	Pass	Pass
bearing capacity of foundation (kPa)	502.99	503.7	579.41	579.7	Pass	Pass

5 Summary and Conclusions

The paper builds the design system of portal structure based on limit state method and develops a software that can significantly improve the design efficiency. Firstly, the limit state equations of portal structure are established based on the reliability theory. Then the partial factors are determined through the target reliability index which obtained from the calibration for railway tunnel general reference map and the design verification. On the base of these, the software based on limit state method is developed by using Visual Basic, which realizes the functions of the reliability index calculation and the structure design based on limit state rapidly.

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