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Research on Design Verification of Limit State Method for Railway Tunnel Lining

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Abstract: In order to explore the feasibility of the limit state method in tunnel lining design, the limit state method and the damage stage method are used to test the design of railway tunnel lining in this paper, then the test results of the two methods are compared and analyzed. Conclusions are as follows: (1) for concrete lining, the calculation thickness obtained from limit state method is higher than that from damage stage method, and the maximum difference reaches 20cm that means it's necessary to get the cracking resistance coefficient (γ_d) of limit state method recalibrated, and the final value is 1.55; (2) for reinforced concrete lining structure and open-cut tunnel structure, the design results base on the limit state method and damage stage method are basically in agreement which means the value of partial coefficient and adjustment coefficient in the limit state equation of reinforced concrete structure are reasonable; (3) the project investment based on the limit state method when the value of γ_d equals 1.55 and damage stage method are basically the same. In terms of all projects that selected, the investment based on limit state method is 2370 thousand and 1% more than that based on damage stage method.

Keywords: railway tunnel lining; limit state method; damage stage method; design verification.

1 Introduction

For a long time, the safety factor method has been adopted in the design of railway tunnel in China (National Railway Administration of the People's Republic of China, 2017), and the limit state method has been widely used as a tunnel design method internationally (Zhao and Yu 2014, Zhao et al. 2015). In order to improve the scientific nature of tunnel design and integrate with international standards, the former Ministry of Railways and the China Railway successively carried out the basic research work on the transition of the design standard of tunnel since 1990s (Zhang et al. 1994, Bian et al. 2005, Qi 2014, Zhao et al. 2015), and published the Interim Code for Limit State Design of Railway Tunnel in 2015(China Railway Corporation, 2015).

Through the reliability calibration of the general reference map of the tunnel, the target reliability indexes of the ultimate bearing capacity of the tunnel lining are put forward referring to the target reliability value of the various industry structures. Based on the target reliability value, the limit state equations of lining structure are proposed in the code. However, the partial factors and adjustment coefficients in code are obtained through the calibration of the general reference map, and not all tunnel sections are designed through the general reference map. So the applicability of limit state method in tunnel design especially for some special cases needs further study. In this paper, the tunnel linings are designed by using limit state method based on interim code and using damage method based on current design code, and the difference of the design results are compared and analyzed. The paper verifies the rationality of limit state method for tunnel lining design and discovers some deficiencies of the interim code which provide reference for its revision.

2 Research Route

At present, the standard design method is adopted under general conditions and standard drawings are used for lining design. The design parameters of standard drawings are obtained based on the numerical calculation combined with engineering experience which leads to the value of the parameters are often safer than the numerical results. The premise of the design verification is that the design method in current code is reasonable and reliable, and the basis for judging the rationality of the limit state method is whether the design result of limit state method is consistent with the results of the damage stage method or not. Therefore, the research route can be summarized as follows:

(ⅰ) Reducing the thickness of original secondary lining 0.25cm every time.

(ⅱ) Calculating the internal force of secondary lining using finite element software based on limit state method and damage stage method respectively.

(ⅲ) Calculating the control index and obtaining the minimum required thickness and quantity of steel bar of secondary lining when the control index reaches the target value.

(ⅳ) Comparing and analyzing the difference of design results of limit state method and damage state method and optimizing the design method.

The control index is bearing capacity when the lining is concrete and the maximum crack width or reinforcement design basis when the lining is reinforced concrete. The checking calculation equations of concrete and reinforced concrete based on limit state method and damage state method can be found in interim code and current code respectively.

3 Calculation Conditions

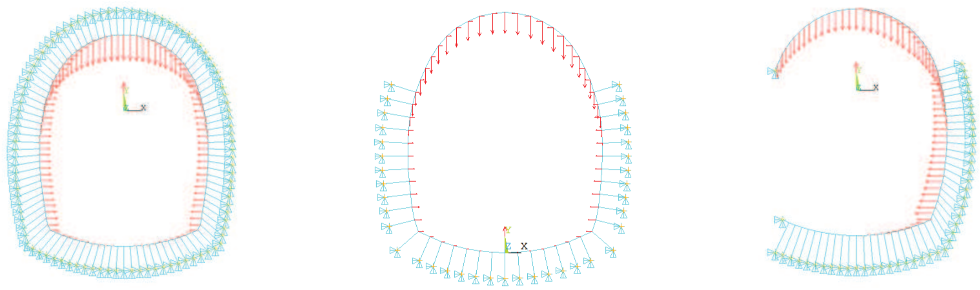
The calculation conditions are listed in Table 1. The selected tunnels contain different types of composite lining and open cut tunnel lining.

Table 1. Calculation conditions

Tunnel	Yongshou-liang tunnel	Bijiashan tunnel	Qishan tunnel	Houshi-shan tunnel	Shangye-tian tunnel	Mawei-shan tunnel	Xinbada-ling tunnel
Rock grade	III~V	III~V	IV~V	III~V	III~V	III~V	II~V
Composite lining	4	11	3	13	8	6	8
Open cut tunnel lining	2	2	2	2	2	2	2
Single/double line	Double	Single	Single	Double	Double	Double	Double
Design speed	350km/h	160km/h	120km/h	200km/h	250km/h	350km/h	250km/h

4 Calculation Models and Parameters

The widely used finite element software ANSYS is adopted in the calculation based on the load-structure model. The lining in the model is simulated by the element type of BEAM3, and contact affection between the lining and surrounding rock is simulated by the type of LINK10. The calculation model of singe line tunnel and open cut tunnel are shown as Fig. 1. The parameters of concrete, steel bar and surrounding rock can be found in section 3.2, 5.2, 5.4 of the interim code and section 4.3, 6.2, 6.4 of the current code.



(a) Secondary lining (b) Bias pressure open cut tunnel (c) single pressure open cut tunnel

Figure 1. Calculation models

5 Analysis of Design Verification

5.1 *Concrete lining*

According to the research route illustrated in Section 2, all of the concrete linings for selected conditions are redesigned. In consideration of the limited space, only the design results of Bijiashan tunnel are listed in Table 2, and the laws of design results of other concrete linings are the same as the Bijiashan tunnel.

Table 2. Calculation results of concrete linings in Bijiashan tunnel

Lining type	Interim code		Current code	
	Arch wall thickness	Control position/mode	Arch wall thickness	Control position/mode
III_a	10cm	Arch crown/anti-cracking	5cm	Arch crown/anti-cracking
IV_b	50cm	Arch crown/anti-cracking	30cm	Arch crown/anti-cracking
IV_a	45cm	Arch crown/anti-cracking	30cm	Arch crown/anti-cracking

Just as shown in Table 2, the two methods have the same control position and mode, but the minimum required thickness of limit state method is higher than that of damage state method for one condition, which means the adjustment coefficient γ_d=2.35 in the checking formula of anti-cracking in interim code is too conservative. Therefore, the adjustment coefficient should be modified.

The γ_d is gradually decreased from 2.35 by 0.05, and when the minimum required thickness of the limit state method is the same as that calculated with the damage stage method, the γ_d can be considered as a suitable value. Taking the concrete lining located in Ⅳ-class surrounding rock as an example, the relation between the lining thickness and the safety factor of the anchor crown section is shown in Figure. 3.

Just as shown in Fig. 2, when using the damage stage method, the thickness of lining h=30cm, the lining passes checking, and the thickness of lining h=25cm, the lining don't pass the checking. When using the limit state method, the relation between γ_d and R-S(R is the resistance and S is the action effect) when h=25cm and h=30cm is as shown in Fig. 3.

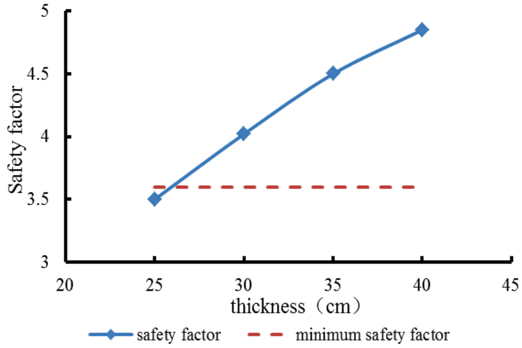


Figure 2. Relation curve of thickness and safety factor

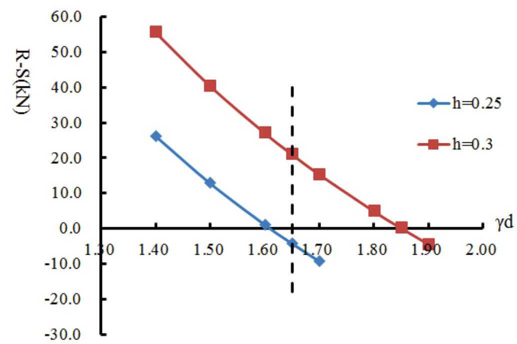


Figure 3. Relation curve of γ_d and R-S

Table 3. Calibration Results of anti-cracking adjustment coefficient

Calculation results	coefficient	140km/h single line Va	160km/h single line IIIa	160km/h single line IVb	160km/h single line IVa	200km/h double line II	200km/h double line III
$h_{LM}=h_{DS}$	γ_d	1.4~1.6	1.4~1.45	1.5~1.65	1.5~1.65	1.45~1.7	1.5~1.6
$h_{LM}>h_{DS}$	γ_d	1.65~1.95	1.5~1.8	1.7~1.85	1.7~1.85	1.75	1.65

In Table 3, the h_{LM} and h_{DS} mean the calculation thickness of lining when using limit state method and damage state method respectively. According to the above calculation results, it is suggested that the γ_d can be adjusted from 2.35 to 1.55, which can ensure the results of the two methods are the same at most conditions and similar in a few cases.

5.2 *Reinforced concrete lining*

The design results of Bijiashan tunnel are listed in Table 4, and the laws of design results of other reinforced concrete linings are the same as the Bijiashan tunnel.

Table 4. Calculation results of reinforced concrete linings in Bijiashan tunnel

Lining type	Interim code			Current code		
	Thickness of lining/cm	Required quantity of rebar/cm^2	Control position/mode	Thickness of lining/cm	Required quantity of rebar/cm^2	Control position/mode
IV	30	5.24	arch crown/ bearing capacity	32.5	5.73	arch crown/ bearing capacity
V_B	37.5	6.23	arch crown/ bearing capacity	37.5	6.6	arch crown/ bearing capacity
V_a	35	4.55	arch crown/ bearing capacity	35	4.61	arch crown/ bearing capacity
V_b	40	6.82	arch crown/ bearing capacity	40	7.13	arch crown/ bearing capacity
V_c	40	6.91	arch waist / bearing capacity	40	5.22	arch waist / bearing capacity
V_d	40	7.71	arch crown/ bearing capacity	40	6.96	arch crown/ bearing capacity

According to Table 4, the design results of the two methods are basically the same. Specifically, the control position and control mode are the same. Besides, the minimum required thicknesses of the two methods are close and the minimum required quantities of steel bars are almost the same, so the final design quantities of reinforcement are completely equal.

In conclusion, the design results of the two methods are basically the same for reinforced concrete lining. Moreover, the design results of open cut tunnel are almost the same as the reinforced concrete lining because the open cut tunnel lining is also made of reinforced concrete.

6 Economic Analysis

According to the results of the above design verification, the investment amount of the main building materials of secondary lining is calculated and the difference of the investment between the two methods is compared in order to analyze the economics of the limit state method. Taking the Bijiashan tunnel as an example, the investment is as shown in Table 5.

Table. 5 Investment and comparison of main building materials in Bijiashan tunnel

Structure	Total investment of tunnel					Investment per meter		
	Length /m	Damage stage method /million	Limit state method /million	Increased /million	Increased proportion	Damage state method /thousand	Limit state method /thousand	Increased /thousand
Concrete lining	2956	12.341	12.341	0	0%	4.18	4.18	0
Reinforced concrete lining	1178	8.403	8.249	-0.154	-1.8%	7.13	7.00	-0.13
Open cut tunnel	8	0.229	0.229	0	0	28.57	28.57	0
Overall length	4142	20.97	20.82	-0.154	-0.73%	50.6	20.3	-0.03

Just as shown in Table 5, the investment of Bijiashan tunnel using limit state method is almost the same with that using damage state method. Considering all the conditions, the total investments of the two methods are basically the same.

7 Conclusions

In this paper, the different types of lining are redesigned by adopting the limit state method and damage stage method respectively. The research results not only verify the operability of limit state method in tunnel design, but also provide the basis for the revision of the interim code.

When the lining structures are made of concrete, the required thickness of lining is different for these two methods. In view of this, the adjustment coefficient of anti-cracking is adjusted from 2.35 to 1.55 which can ensure the design results of two methods keep consistent in most cases. For reinforcement concrete lining, the required thickness of lining and quantity of rebar are almost the same. Therefore, the factors in limit state equations of reinforcement concrete are reasonable. From the economic analysis result, the tunnel total investments of two methods are almost the same when adopting the calibrated adjustment coefficient of concrete anti-cracking.

In summary, the design results of two methods are basically the same after correcting the adjustment coefficient of anti-cracking.

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