Stability evaluation method of large cross-section tunnel considering modification of thickness-span ratio in mechanized operation

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Abstract

Purpose – This study aims to research the large cross-section tunnel stability evaluation method corrected after considering the thickness-span ratio.

Design/methodology/approach – First, taking the Liuyuan Tunnel of Huanggang-Huangmei High-Speed Railway as an example and taking deflection of the third principal stress of the surrounding rock at a vault after tunnel excavation as the criterion, the critical buried depth of the large section tunnel was determined. Then, the strength reduction method was employed to calculate the tunnel safety factor under different rock classes and thickness-span ratios, and mathematical statistics was conducted to identify the relationships of the tunnel safety factor with the thickness-span ratio and the basic quality (BQ) index of the rock for different rock classes. Finally, the influences of thickness-span ratio, groundwater, initial stress of rock and structural attitude factors were considered to obtain the corrected BQ, based on which the stability of a large cross-section tunnel with a depth of more than 100 m during mechanized operation was analyzed. This evaluation method was then applied to Liuyuan Tunnel and Cimushan No. 2 Tunnel of Chongqing Urban Expressway for verification.

Findings – This study shows that under different rock classes, the tunnel safety factor is a strict power function of the thickness-span ratio, while a linear function of the BQ to some extent. It is more suitable to use the corrected BQ as a quantitative index to evaluate tunnel stability according to the actual conditions of the site.

Originality/value – The existing industry standards do not consider the influence of buried depth and span in the evaluation of tunnel stability. The stability evaluation method of large section tunnel considering the correction of overburden span ratio proposed in this paper achieves higher accuracy for the stability evaluation of surrounding rock in a full or large-section mechanized excavation of double line high-speed railway tunnels.

Keywords Large cross-section tunnel, Mechanized operation, Tunnel stability, Thickness-span ratio, Basic quality index of rock, Safety factor, Depth, Span

Paper type Research paper

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1. Introduction

In recent years, with the increasing demand for traffic infrastructure in China, tunnel construction faces greater challenges and higher requirements. To ensure the safety of tunnel construction with better working conditions, higher working efficiency and less labor intensity, large-scale mechanized tunneling technologies come into being.

In large-scale mechanized tunnel construction, the "mechanized construction" is the core, and the mechanized working lines such as drill jumbo, wet spraying jumbo, hydraulic inverted arch trestle, waterproof board and reinforcement installation and positioning rack, hydraulic lining jumbo, groove sliding formwork jumbo and lining curing jumbo are used; the tunneling method and support means are dynamically adjusted according to advance geological forecast and the comprehensive analysis of the monitoring and measurement results. Compared with the traditional tunneling method, large-scale mechanized tunneling can control rock deformation more effectively and improve the stress characteristics of supporting structures (Huang, Chen, Zhang, & Ma, 2020; Jin, Wang, Zhu, Liu, & Zhang, 2020; Zhang, 2017; Yu & Cai, 2018), create greater economic benefits (Wu, Qin, & Luo, 2020; Wei, 2012) and have a wider application prospect.

To realize large-scale mechanized construction, the tunnel shall be excavated by the full-section or large cross-section method, so the tunnel rock stability matters. According to the *Code for Design of Railway Tunnel* (TB 10003-2016, hereinafter referred to as the *Code*), tunnel stability is mainly evaluated by rock BQ (National Railway Administration of the People's Republic of China, 2016), and this method is called BQ method, which refers to calculating rock BQ in terms of two indexes: the uniaxial compressive strength of rock and the rock mass integrity, correcting BQ after further considering the groundwater state, initial geostress state, occurrence of main structural planes and other relevant factors, and then quantitatively evaluating the tunnel stability by the corrected value of rock quality index.

This method is simple and convenient, commonly used for quantitative evaluation of tunnel stability, so it has been widely applied in tunneling practice and research for years. However, the depth and span of tunnel have non-negligible influences on the tunnel rock stability (Sun, Zheng, Wang, Zhang, & Zhang, 2012; Chen, Ye, Meng, & Yu, 2011) which are not considered in the existing BQ method for tunnel stability evaluation. Therefore, the method is not quite applicable to large cross-section mechanized tunneling and is difficult to accurately guide the stability analysis for large cross-section tunnel. Hence, it is necessary to correct the existing BQ method for a better quantitative evaluation of tunnel stability in large cross-section mechanized tunneling.

Sun *et al.* (2012) studied the influence of tunnel depth on rock classification standards by numerical simulation and established a relationship among rock parameters and safety factors and rock classes, which improves the BQ method for tunnels with a depth of 100–2,500 m, which has certain engineering significance. Liu, Sun, Zuo, and Yuan (2015) identified the influence of weak intercalated layer on the results of tunnel stability evaluation with the BQ method and corrected the rock classification accordingly. The results of the corrected rock classification are quite consistent with the actual rock class in practice. Ren, Li, Zhang, Niu, and Lin (2011) studied the high geostress and other influencing factors in the employment of the BQ method, considered the influences of large deformation and rock burst, and on this basis, obtained the geostress reduction factor under large deformation and rock burst conditions, thus improving the applicability of the BQ method under high geostress. To sum up, some scholars have realized the insufficiency of the existing BQ methods and have put forward some correction methods after considering different factors. However, they did not comprehensively consider the influences of depth and span on the calculation of BQ.

For the purpose of this paper, the Liuyuan Tunnel of Huanggang-Huangmei High-Speed Railway was taken as an example, where the actual depth of the tunnel and the current study of BQ correction based on the depth were considered; and a stability evaluation method corrected for large cross-section tunnels considering the thickness-span ratio under the mechanized operation condition was proposed for double-track high-speed railway tunnel with a depth more than 100 m and a speed of 350 km/h.

2. Determination of critical depth of long-span tunnel

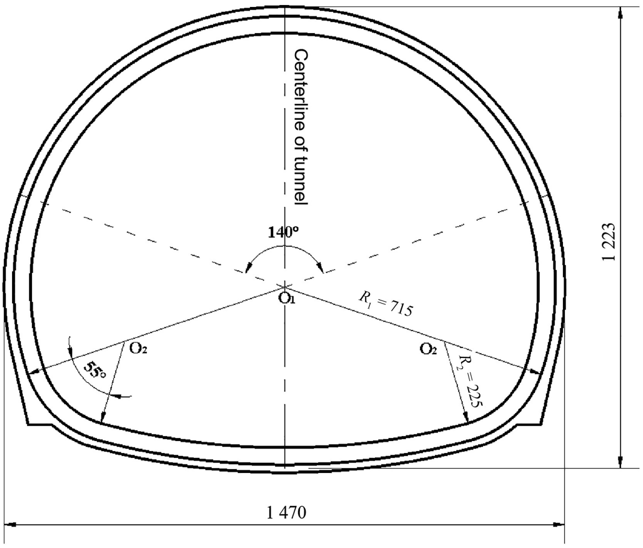
For the purpose of this paper, the Liuyuan Tunnel of Huanggang-Huangmei High-Speed Railway was taken as an example; and the double-track high-speed railway tunnel section with an excavation span of 14.7 m and a speed of 350 km/h was selected as the calculation model shown in Figure 1. In the figure, O_1, O_2 and O_3 are the center of each arc of the multi-center circle, respectively, and R is the radius of each arc of the multi-center circle. By changing the tunnel depth to change the thickness-span ratio, this paper studied the relationship between the rock BQ and the thickness-span ratio when the tunnel depth varies from the boundary that divides deep tunnel and shallow tunnel (National Railway Administration of the People's Republic of China, 2016) (critical depth) to 100 m, that is, the thickness-span ratio changed from the critical thickness-span ratio to about 7. Therefore, accurately determining the critical depth of the tunnel is the basis for studying the influence of the thickness-span ratio on the stability of a large-span tunnel.

The method for determining the critical depth given in the *Code* based on the statistical average collapse height and design experience is expressed as follows:

$$H_{cr} = 2.5h_{\mathrm{a}} \tag{1}$$

where H_{cr} is the critical depth; h_{a} is the height of the vertical load of the deep tunnel, which is calculated according to Appendix D of the Code for Design of Railway Tunnel (TB10003-2016).

However, due to the limitations of the statistical method and statistical samples, the method used to determine the critical depth in Equation (1) is not quite applicable to large cross-section tunnels (Qing, Zhang, & Zhu, 2013).



Source(s): Authors own work

Figure 1.
Dimensions of tunnel section (unit: cm)

With the progress of pressure arch theory, the method that divides deep and shallow tunnels according to the critical arching depth where the rock can just form a pressure arch has been widely recognized (Qing *et al.*, 2013; Li, Li, & Gao, 2013; Qu, 2020). Li, Zhang, Song, Fang, and Chen (2012), Hu and Zhang (2012) and Song (2016) used the portion where the third principal stress deflection occurs as the outer boundary of the pressure arch, that is, after tunnel excavation, the third principal stress deflection occurs at a height between the tunnel vault and the ground surface is a necessary condition for forming the pressure arch after excavation. On this basis, Qu (2020) proposed a numerical method for determining the pressure arch range and critical tunnel depth and calculated and made statistics of the horizontal stresses and vertical stresses of the rock within the range from the tunnel vault to the ground surface under different depth conditions. If the horizontal stress curve is tangent to the vertical stress curve under a depth condition, the result indicates that the third principal stress deflection can occur under Qu's proposed depth condition, and such a depth is the critical one where the pressure arch can just form, i.e. the critical depth that divides deep and shallow tunnels. In this paper, this method was used to establish a two-dimensional plane Mohr-Coulomb (M-C) criterion model by finite difference numerical method; and physical and mechanical values recommended in the *Code* were selected as the calculation parameters to study the critical depth of the double-track high-speed railway tunnel with an excavation span of 14.7 m for different rock classes. The calculation model is shown in Figure 2.

In order to illustrate how the critical depth is determined, Class IV rock was taken as an example to calculate the horizontal stress and vertical stress at each monitoring point within the range from the tunnel vault to the surface for different depths. The vault is regarded as the origin of coordinates, the abscissa represents the distance between the measuring point and the vault, and the ordinate represents the stress value under different depth. The stress variation curves of the path above the tunnel vault under different depth conditions in Class IV rock are shown in Figure 3.

Figure 3 shows that when the depth is 22 m, the horizontal stress on the path above the arch crown after tunnel excavation is in the direction of the major principal stress, and there is no intersection point between the two curves. This indicates that in this case, the direction of the major principal stress is not deflected, the boundary of the pressure arch cannot be formed, and the tunnel is a shallow tunnel. When the depth is 26 m, the two curves on the path above the arch crown after tunnel excavation are tangent to each other, and the major principal stress is within the limit state of deflection, indicating that this depth is the critical depth that divides deep tunnel and shallow tunnel. When the depth is 40 m, the two curves on the path above the arch crown intersect after the tunnel is excavated, indicating that the direction of the major principal stress at the intersection point deflects, and that the tunnel is a deep tunnel. That is to say, in the case of Class IV rock, when the depth is greater than 26 m, the tunnel will be a deep tunnel.

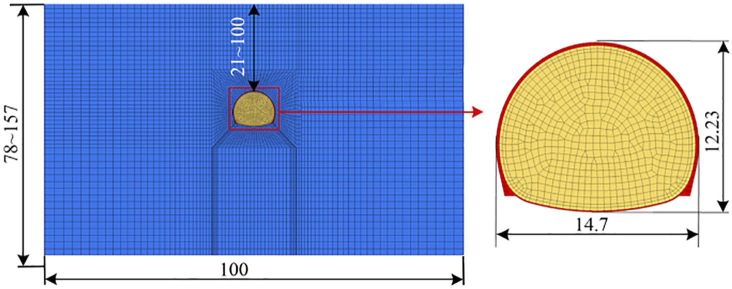


Figure 2.
Calculation model
(unit: m)

Source(s): Authors own work

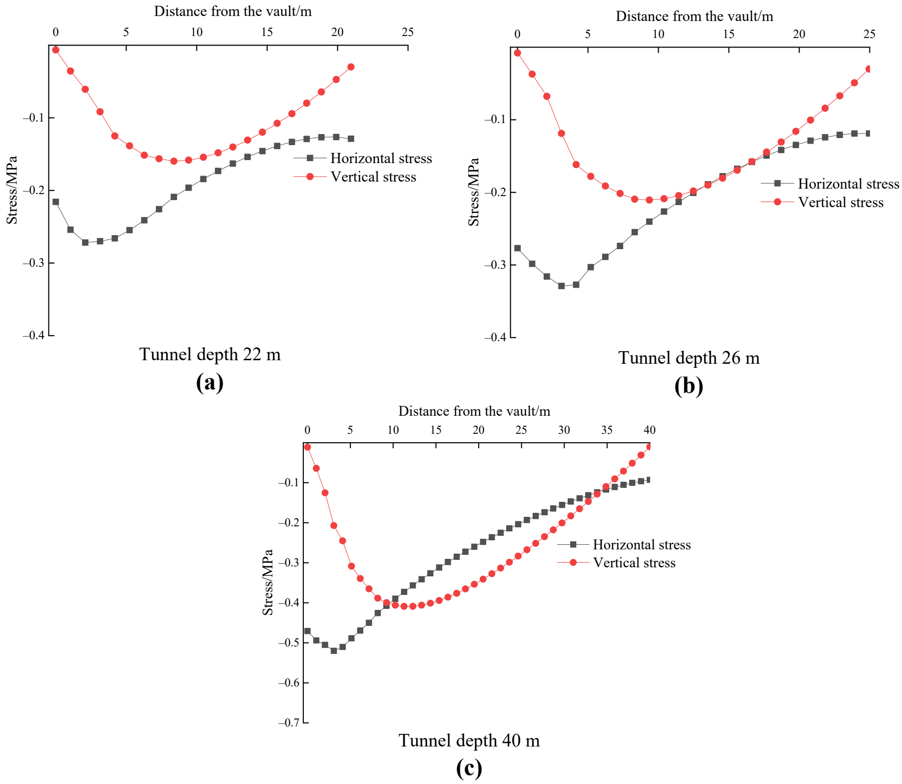


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Figure 3.
Stress variation curves of path above tunnel vault in Class IV rock for different depths (Span $B = 14.7$ m)

Through further calculation, the critical depth of the double-track high-speed railway tunnel with a span of 14.7 m under different rock classes is obtained, and the comparison with the critical depth and critical thickness-span ratios calculated according to the *Code* is shown in Table 1.

Table 1 shows that for a double-track high-speed railway tunnel with a span of 14.7 m, in the cases of Class II, III and IV rocks, the calculated values of the critical depth are greater than those calculated according to the *Code* (code value), and that the better the rock is, the greater the difference will be. The differences between the calculated values and the code values are 16.6, 14.1 and 8.3 m, respectively. In the case of Class V rock, the calculated values

	Numerical calculation results		Results calculated according to the *Code*	
Rock class	Critical depth/m	Critical thickness-span ratio	Critical depth/m	Critical thickness-span ratio
II	21.0	1.43	4.4	0.30
III	23.0	1.56	8.9	0.60
IV	26.0	1.77	17.7	1.20
V	33.0	2.24	35.5	2.40

Source(s): Authors own work

Table 1.
Critical depths of double-track high-speed railway tunnel (Span $B = 14.7$ m)

are slightly lower than the code values, with a difference of −2.5 m. Therefore, this numerical calculation method can provide a reference for the division of deep and shallow tunnels of double-track high-speed railway.

3. Correlation between safety factor and rock BQ and thickness-span ratio of long-span tunnel

Yang, Zheng, Zhang, Wang, and Song (2009), Zhang, Zheng, Wang, and Wang (2007), Zheng, Qiu, Zhang, and Wang (2008) and Zhang, Zheng, Yang, and Wang (2009) introduced the concept of safety factor into the stability analysis of rock tunnels by the strength reduction method. The safety factor has certain mechanical significance and can be used as a quantitative index for tunnel stability evaluation. In the study, the author calculated the safety factor of the gross tunnel under each condition where the critical thickness-span ratio under each rock class is approximately equal to 7 by the strength reduction method and established the mathematical relationship between the safety factor and the thickness-span ratio under each rock class.

3.1 Principle and instability criteria of strength reduction method

The strength reduction method is to analyze the change rules of the characteristic points in continuously reducing the internal friction angle and cohesion of the rock until the indexes analyzed indicate that the rock is in the instability limit state, and then define the rock strength reduction coefficient F_s at this moment as the safety factor. The internal friction angle and cohesion in the strength reduction method are as follows:

$$\varphi' = \arctan\frac{\tan\varphi}{F_s} \tag{2}$$

$$c' = \frac{c}{F_s} \tag{3}$$

where φ' is the internal friction angle after reduction; φ is the friction angle without reduction; c' is the cohesion after reduction; and c is the cohesion without reduction.

The key point for calculating the tunnel safety factor by the strength reduction method is to select a reasonable instability criterion to determine whether the tunnel rock is in the critical limit equilibrium state. Currently, three instability criteria are available.

1. Penetration of plastic zone. Generally speaking, penetration of plastic zone is a necessary but insufficient condition for tunnel instability. When only penetration of the plastic zone is used as the criterion, the tunnel safety factor obtained will be smaller than the actual value.
2. Convergence of calculation. When this criterion is used, the calculation accuracy and the number of steps need to be set manually, which is subjective to change and the calculation results may not be accurate. Meanwhile, the calculation model grid and calculation software also have a certain impact on the convergence of the calculation.
3. Abrupt change in the displacement of characteristic points. During site construction, the workers often judge tunnel stability according to the displacement monitoring data of the characteristic points of the tunnel (arch crown, perimeter and inverted arch).

Compared with the other two criteria, abrupt changes in the displacement of characteristic points are more realistic and objective as the criterion of instability, and more applicable to the actual conditions. Therefore, abrupt changes in the displacement of characteristic points (arch crown, haunch, spandrel, inverted arch, etc.) are selected as the main criterion for tunnel rock instability.

3.2 Correlation between safety factor and thickness-span ratio of tunnel

A two-dimensional plane M-C criterion model is established through the finite difference numerical calculation by applying the strength reduction method, to study the safety factors of the tunnel under each rock class when the thickness-span ratio varies from the critical thickness-span ratio to about 7 (corresponding to the depth of 102.9 m). The calculation results are shown in Table 2.

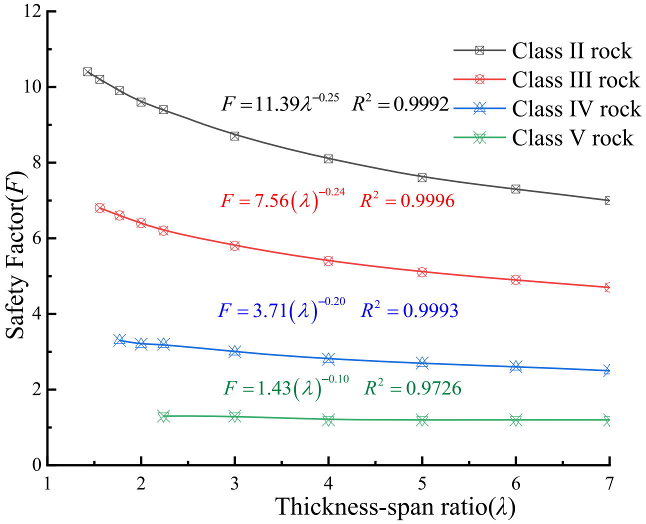
According to the calculation results in Table 2, the relationship curve between the safety factor and the thickness-span ratio of the tunnel under different rock classes can be obtained, as shown in Figure 4, where F is the safety factor of the tunnel; λ is the thickness-span ratio, i.e. H/B (H is the depth); and R^2 is the linear correlation coefficient.

Figure 4 shows that the fitted curve of the safety factor F and the thickness-span ratio of the tunnel for a certain rock class is in the form of a power function, and the correlation coefficients are high, indicating the fitting formula is reasonable and reliable. For a

Depth/m	Thickness-span ratio	Safety factors of the tunnel under different rock classes			
		II	III	IV	V
21.0	1.43	10.4			
23.0	1.56	10.2	6.8		
26.0	1.77	9.9	6.6	3.3	
29.4	2.00	9.6	6.4	3.2	
33.0	2.24	9.4	6.2	3.2	1.3
44.1	3.00	8.7	5.8	3	1.3
58.8	4.00	8.1	5.4	2.8	1.2
73.5	5.00	7.6	5.1	2.7	1.2
88.2	6.00	7.3	4.9	2.6	1.2
102.9	7.00	7.0	4.7	2.5	1.2

Source(s): Authors own work

Table 2. Safety factors of tunnel with different thickness-span ratios under different rock classes



Source(s): Authors own work

Figure 4. Relationship between safety factor and thickness-span ratio

certain rock class, the tunnel safety factor decreases with the increase of the thickness-span ratio, indicating the increase of the thickness-span ratio is not conducive to tunnel stability.

When the rock BQ is calculated according to the method in the *Code*, if the uniaxial compressive strength of rock, rock mass integrity and the correction coefficient are fixed, any change of the thickness-span ratio will not affect the value of BQ. Since both the safety factor and BQ are quantitative indexes reflecting tunnel stability, their change rules shall be similar. It is proved again that the influence of thickness-span ratio is not considered in the BQ method in the *Code*, resulting in a certain limitation on the stability evaluation of large cross-section tunnels.

3.3 Correlation between rock BQ and thickness-span ratio of tunnel

In the *Code*, a specific BQ range corresponds to a certain rock class, but rock BQ is related to the uniaxial compressive strength of rock and the rock mass integrity only, not the thickness-span ratio. Therefore, when studying the correlation between BQ and thickness-span ratio, the BQ of a certain rock class was approximately considered a constant, and the upper limit of the value range in the *Code* was taken for analysis. The BQs of Class II, III, IV and V rocks are 550, 450, 350 and 250, respectively.

It can be seen from Table 2 that, for a specific rock class, the safety factor corresponding to the critical thickness-span ratio is the largest, and will decrease with the increase of the thickness-span ratio. Therefore, the tunnel safety factor corresponding to a thickness-span ratio can be regarded as the safety factor calculated on the basis of the critical thickness-span ratio and then corrected considering the influence of thickness-span ratio. Accordingly, this rock BQ can also be regarded as the rock BQ first calculated according to the *Code* and then corrected considering the influence of thickness-span ratio. This proves the correlation between rock BQ and safety factors once again.

The calculated BQ values and safety factors F_{critical} under critical thickness-span ratio under different rock classes are shown in Table 3.

The following mathematical relationship between rock BQ and safety factor can be obtained by fitting the data in Table 3:

$$I_{\text{BQ}} = 32.14F + 225 \tag{4}$$

where I_{BQ} is the rock BQ value.

The correlation coefficient of the above formula is 0.9843, indicating the safety factor is a linear function of the BQ value to some extent.

4. Calculation of rock BQ of large cross-section tunnel corrected considering thickness-span ratio

The rock BQ calculation formula in the *Code* is

Table 3.
BQ values of different rock classes and safety factors at critical thickness-span ratio

Rock class	I_{BQ}	F_{critical}
II	550	10.39
III	450	6.77
IV	350	3.32
V	250	1.33

Source(s): Authors own work

$$I_{\mathrm{BQ}} = 100 + 3R_{\mathrm{c}} + 250K_{\mathrm{v}} \tag{5}$$

where R_{c} is the saturated uniaxial compressive strength of rock and K_{V} is the rock mass integrity index.

The corrected BQ value I'_{BQ} considering the influences of groundwater, main weak structural planes and initial geostress is

$$I'_{\mathrm{BQ}} = I_{\mathrm{BQ}} - 100(K_1 + K_2 + K_3) \tag{6}$$

where K_1, K_2 and K_3 are the correction coefficients for groundwater, structural plane occurrence and initial geostress state, respectively.

According to the relationship curves between safety factors of different rock classes and the thickness-span ratios in Figure 4 and Equation (4), the mathematical relationship of BQ with thickness-span ratio considered under different rock classes can be obtained.

The BQ value $I_{\mathrm{BQ,II}}$ of Class II rock with the thickness-span ratio considered is expressed as

$$I_{\mathrm{BQ},II} = 366\lambda^{-0.25} + 225 \tag{7}$$

The BQ value $I_{\mathrm{BQ,III}}$ of Class III rock with the thickness-span ratio considered is expressed as

$$I_{\mathrm{BQ},III} = 243\lambda^{-0.24} + 225 \tag{8}$$

The BQ value $I_{\mathrm{BQ,IV}}$ of Class IV rock with the thickness-span ratio considered is expressed as

$$I_{\mathrm{BQ},IV} = 119\lambda^{-0.20} + 225 \tag{9}$$

The BQ value $I_{\mathrm{BQ,V}}$ of Class V rock with the thickness-span ratio considered is expressed as

$$I_{\mathrm{BQ},V} = 46\lambda^{-0.10} + 225 \tag{10}$$

Equations (7)–(10) are used to calculate the corrected BQ considering the influence of thickness-span ratio in the mechanized operation of large cross-section tunnels under different rock classes.

In the application, we can calculate the value of the rock basic quality index $I_{\mathrm{BQ},\lambda}$ considering the influence of the thickness-span ratio according to the above calculation formulas and then calculating the corrected value $I'_{\mathrm{BQ},\lambda}$ of the rock basic quality index considering the influence of groundwater, main weak structural planes and initial geostress. The calculation formula is expressed as

$$I'_{\mathrm{BQ},\lambda} = I_{\mathrm{BQ},\lambda} - 100(K_1 + K_2 + K_3) \tag{11}$$

Similarly, according to the *Code*, $I'_{\mathrm{BQ},\lambda}$ can be determined as a quantitative index to evaluate tunnel stability.

5. Method validation

In order to validate the applicability and correctness of the BQ calculation method corrected considering the thickness-span ratio, it was used to evaluate the stability of section DK90 + 060.0–DK90 + 080.0 of Liuyuan Tunnel of Huanggang-Huangmei High-Speed Railway and section ZK3+105.0–ZK3+543.4 of Cimushan No.2 Tunnel of Chongqing Expressway. Then, the calculation results were compared with the results obtained by applying the BQ calculation method in the *Code* and the class of the rock actually supported on site.

5.1 Application in Liuyuan Tunnel for validation

Liuyuan Tunnel is located in Dajin Town, Wuxue City, Hubei Province. The chainages of the entrance and exit of the tunnel are DK90 + 660.0 and DK91 + 265.0, respectively, with a total length of 605 m and a maximum excavation span of 14.7 m. It is located in a hilly area with well-developed vegetation. The maximum depth is 89.0 m.

The main lithology in the tunnel area features from completely to moderately weathered quartz schist, with an average saturated uniaxial compressive strength of 39.8 MPa. The surface water is weakly developed, and a small amount of inter-hill streams exist in some valleys and are relatively developed only in the rainy season. Atmospheric precipitation is the source to supplement the groundwater, and surface water is non-corrosive and weakly developed. The rock classes of Liuyuan Tunnel are shown in Table 4.

5.1.1 Calculation indexes.

(1) Saturated uniaxial compressive strength of rock

The field sampling test shows the saturated uniaxial compressive strength of rock is 39.8 MPa.

(2) Rock mass integrity index

According to the results of the advance forecast system (TSP) for section DK90 + 060.0–DK90 + 080.0 of Liuyuan Tunnel, the rock mass integrity index of this section was determined to be 0.55 according to Table B.1.3-1 of the Code for Design of Railway Tunnel (TB10003-2016).

(3) Correction factor for influence of groundwater

According to the geological sketch record of tunnel face in section DK90 + 060.0–DK90 + 080.0, the rock of this section is quartz schist, and water seepage can be observed at some positions on the tunnel face. By reference to Table B.2.3-1, of the Code for Design of Railway Tunnel (TB10003-2016) K_1 was determined to be 0.2.

(4) Correction factor for influence of structural plane occurrence

According to the geological sketch record of tunnel face in section DK90 + 060.0–DK90 + 080.0 and in combination with the comprehensive analysis in Table B.2.3-3 of the Code for Design of Railway Tunnel (TB10003-2016), K_2 was determined to be 0.2.

(5) Correction factor for influence of initial stress state

If the rock has no initial geostress state, the evaluation can be conducted according to Table B.2.2-3 of the Code for Design of Railway Tunnel (TB10003-2016) on the basis of $\frac{R_c}{\sigma_{\max}}$, where R_c is the uniaxial compressive strength of rock; and $\sigma_{\max}$ is the maximum value of initial geostress in the direction perpendicular to the tunnel axis. Since $R_c = 39.8$ MPa, tunnel depth is 30 m, and calculated $\frac{R_c}{\sigma_{\max}} > 7$, being general geostress, so that $K_3 = 0$ was determined.

5.1.2 Evaluation results. The tunnel stability was evaluated according to the rock BQ calculation method in the *Code* and the BQ calculation method corrected considering the thickness-span ratio respectively.

For section DK90 + 060.0–DK90 + 080.0, the thickness-span ratio of the tunnel is $\lambda = \frac{30}{14.7} = 2.04$, and the rock class is Class IV. Therefore, in the calculation where the thickness-

Table 4.
Proportions of different rock classes of Liuyuan Tunnel

Rock class	Length/m	Proportion/%
III	160	20.9
IV	270	35.4
V	333	43.7

Source(s): Authors own work

span ratio is considered, the rock BQ was calculated by Equations (9) and (11). The results obtained by the two calculation methods are shown in Table 5.

Table 5 shows that when the BQ calculation method in the *Code* was adopted, the corrected value of the rock basic quality index obtained is 317, and the rock class was judged as Class IV_1. When the rock BQ calculation method corrected considering the thickness-span ratio was adopted, the corrected rock BQ value was 288, and the rock class was judged as Class IV_2.

During the actual construction, Class IV reinforced support measures were adopted for section DK90 + 060.0−DK90 + 080.0 of Liuyuan Tunnel. Therefore, tunnel stability analysis by the corrected BQ considering the thickness-span ratio is more applicable to the actual conditions of the site.

5.2 Application in Cimushan No.2 Tunnel for validation

The stability of ZK3+105.0−ZK3+543.4 section of Cimushan No.2 Tunnel was evaluated with the BQ calculation method in the *Code* and the BQ calculation method corrected considering the thickness-span ratio, respectively, and the stability evaluation results were compared with the actual supports on site.

Liu *et al.* (2015) give the calculation results of relevant indexes of Cimushan No.2 Tunnel, as shown in Table 6; while Table 7 indicates the calculation results of typical sections of Cimushan No.2 Tunnel.

Table 5. Comparison of calculation results obtained by two methods

Thickness-span ratio	Method in the code			Corrected method considering thickness-span ratio		
	I_{BQ}	I'_{BQ}	Rock class	$I_{BQ,\lambda}$	$I'_{BQ,\lambda}$	Rock class
2.04	357	317	IV_1	328	288	IV_2

Source(s): Authors own work

Table 6. Technical indexes of typical sections of Cimushan No.2 Tunnel

Chainage	R_c/MPa	K_V	K_1	K_2	K_3	Thickness-span ratio
ZK3+105.0—ZK3+124.1	41.1	0.72	0.1	0.1	0	3.75
ZK3+124.1—ZK3+147.0	41.1	0.70	0.1	0.2	0	3.75
ZK3+147.0—ZK3+158.5	41.1	0.70	0.1	0.2	0	3.75
ZK3+158.5—ZK3+202.2	41.1	0.72	0.1	0.1	0	3.75
ZK3+202.2—ZK3+211.7	41.1	0.72	0.1	0.1	0	3.75
ZK3+211.7—ZK3+251.4	41.1	0.72	0.1	0.2	0	3.75
ZK3+251.4—ZK3+275.7	25.0	0.60	0.2	0.1	0	3.75
ZK3+275.7—ZK3+296.7	25.0	0.60	0.2	0.1	0	3.75
ZK3+296.7—ZK3+316.6	25.0	0.60	0.2	0.1	0	3.75
ZK3+316.6—ZK3+337.4	25.0	0.60	0.2	0.1	0	3.75
ZK3+337.4—ZK3+360.0	41.1	0.72	0.1	0.2	0	3.75
ZK3+360.0—ZK3+365.0	41.1	0.72	0.1	0.2	0	3.75
ZK3+365.0—ZK3+373.0	41.1	0.72	0.1	0.2	0	3.75
ZK3+373.0—ZK3+384.7	41.1	0.72	0.1	0.2	0	3.75
ZK3+384.7—ZK3+415.3	41.1	0.75	0.1	0.1	0	3.75
ZK3+415.3—ZK3+430.0	41.1	0.72	0.1	0.2	0	3.75
ZK3+516.0—ZK3+530.6	41.1	0.75	0.1	0.2	0	3.75
ZK3+530.6—ZK3+543.4	41.1	0.72	0.1	0.1	0	3.75

Source(s): Figure courtesy of Liu *et al.* (2015)

Table 7.
Calculation results of typical sections of Cimushan No.2 Tunnel

		BQ calculation method in the *Code*		Corrected BQ calculation method considering the thickness-span ratio		
Section number	Chainage	I'_{BQ}	Rock class	$I'_{BQ,\lambda}$	Rock class	Class of actual supporting rock (Liu *et al.*, 2015)
1	ZK3+105.0—ZK3+124.1	373	III	296	IV	Reinforced Class III
2	ZK3+124.1—ZK3+147.0	358	III	286	IV	IV
3	ZK3+147.0—ZK3+158.5	358	III	286	IV	IV
4	ZK3+158.5—ZK3+202.2	373	III	296	IV	Reinforced Class III
5	ZK3+202.2—ZK3+211.7	373	III	296	IV	Reinforced Class III
6	ZK3+211.7—ZK3+251.4	363	III	286	IV	IV
7	ZK3+251.4—ZK3+275.7	285	IV	286	IV	IV
8	ZK3+275.7—ZK3+296.7	285	IV	286	IV	IV
9	ZK3+296.7—ZK3+316.6	285	IV	286	IV	IV
10	ZK3+316.6—ZK3+337.4	285	IV	286	IV	IV
11	ZK3+337.4—ZK3+360.0	363	III	286	IV	IV
12	ZK3+360.0—ZK3+365.0	363	III	286	IV	IV
13	ZK3+365.0—ZK3+373.0	363	III	286	IV	IV
14	ZK3+373.0—ZK3+384.7	363	III	286	IV	IV
15	ZK3+384.7—ZK3+415.3	380	III	381	III	Reinforced Class III
16	ZK3+415.3—ZK3+430.0	363	III	286	IV	IV
17	ZK3+516.0—ZK3+530.6	370	III	371	III	Reinforced Class III
18	ZK3+530.6—ZK3+543.4	373	III	296	IV	Reinforced Class III

Source(s): Authors own work

Table 7 and Figure 5 show that the rock classes obtained by the BQ calculation method in the *Code* were mainly Class III and a few Class IV, while those obtained by the BQ calculation method corrected considering the thickness-span ratio were mainly Class IV and some

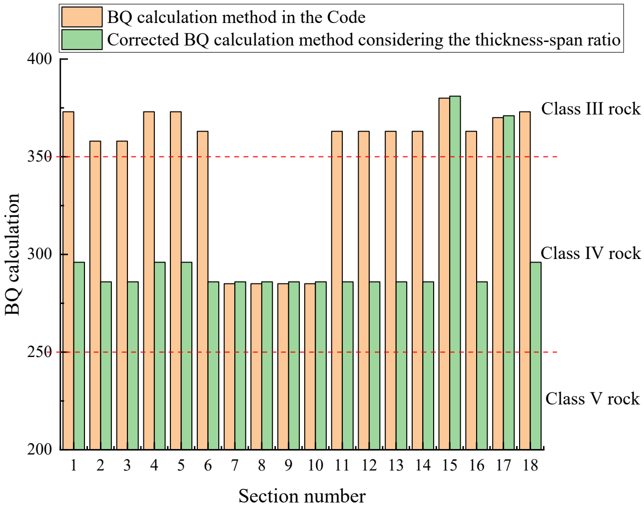


Figure 5.
Calculation results of typical sections of Cimushan No.2 Tunnel

Source(s): Authors own work

Class III. Different rock classes were obtained for 12 sections by the two methods. By comparing the rock classes with the actual support measures on site, the results obtained by the BQ calculation method corrected considering the thickness-span ratio are more applicable to the actual conditions of the site.

6. Conclusions

(1) The strength reduction method is applied to the stability analysis of tunnel rock, and the abrupt changes in the displacement of characteristic points are used as the rock instability criterion, to obtain the safety factors of large cross-section tunnels with different thickness-span ratios under different rock classes in mechanized operation. The mathematical relationship (i.e. a strict power function relationship) between the tunnel safety factor and the thickness-span ratio is established,

(2) The mathematical relationship (i.e. a certain linear relationship) between the tunnel safety factor and the rock BQ is established. In combination with the mathematical relationship between the tunnel safety factor and the thickness-span ratio, the functional relationship between the rock BQ and the thickness-span ratio is obtained; and on this basis, the rock BQ calculation method corrected considering the thickness-span ratio for large cross-section tunnels in mechanized operation is obtained.

(3) The rock BQ calculation method corrected considering the thickness-span ratio is adopted to obtain the corrected rock BQ. As a quantitative index for evaluating the tunnel stability, the corrected rock BQ is used to evaluate the section DK90 + 060.0−DK90 + 080.0 of Liuyuan Tunnel of Huanggang-Huangmei High-Speed Railway and section ZK3+105.0−ZK3+543.4 of Cimushan No.2 Tunnel of Chongqing Expressway. The results show that the evaluation results of the corrected method considering the thickness-span ratio are more applicable to the actual conditions.

(4) The corrected BQ calculation formula considering the thickness-span ratio is slightly complicated and can be further studied in prospective research. For example, the thickness-span ratio correction coefficient K_4 can be introduced to simplify the formula in form in order to obtain an expression form similar to that in the *Code*.

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