ChinaRxiv 中X

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202511.00040

Calculation Method for Support Force of Full-Length Prestressed Rock Bolts Considering Shear Performance Postprint

Authors: Zhimin Chen

Date: 2025-11-01T00:00:00+00:00

Abstract

To investigate the shear resistance performance of full-length prestressed anchor bolts against shear slip masses, a method for calculating the minimum support resistance required for slip masses was proposed based on shear slip theory. The neutral point position and support force calculation method for full-length prestressed anchor bolts were derived and applied to a tunnel case study to verify its rationality. The results indicate that: compared with traditional methods, the approach using slip mass area and surrounding rock grade to calculate the minimum required resistance is simpler and provides a higher safety margin. Within the specified range: increasing the anchor bolt diameter shifts the neutral point position toward the bolt tail; increasing the prestress shifts it toward the bolt head. Although these two factors have different effects on the neutral point position, both can proportionally increase the axial force in the anchor bolt and the radial support resistance. When bolt-shotcrete support is employed, the radial support resistance provided by the anchor bolt is minimal. It is recommended that anchor bolt parameters be designed based on the shear force at the slip surface, with appropriate increases in diameter and prestress to improve shear resistance performance while simultaneously enhancing radial support resistance. The research findings can serve as a reference for calculating the shear resistance performance of full-length prestressed anchor bolts.

Full Text

Calculation Method of Support Force of Full-Length Prestressed Bolt Considering Shear Performance

CHEN Zhimin[1], WANG Hong[1], LI Yazi[2], GONG Jun[3], LI Zengyin[3]
[1]School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou 730070,

China [2]China Construction Eighth Engineering Division Rail Transit Construction Co., Ltd., Nanjing 210046, China [3]China Railway Tunnel Bureau Group Co., Ltd., Guangzhou 511458, China

Abstract: To investigate the shear resistance of full-length prestressed bolts against shear-slip bodies, this study proposes a method for calculating the minimum support resistance required for slip bodies based on shear-slip theory. The neutral point position and support force calculation method for full-length prestressed bolts are derived and validated through a tunnel case study. The results demonstrate that calculating the minimum required resistance using the slip body area and rock mass classification is simpler and provides higher safety margins than traditional methods. Within specified ranges, increasing the bolt diameter shifts the neutral point toward the bolt tail, while increasing prestress moves it toward the bolt head. Although these parameters affect the neutral point position differently, both proportionally increase the bolt axial force and radial support resistance. When using shotcrete-bolt support, the radial support resistance provided by bolts is relatively small. It is recommended to design bolt parameters based on shear values at the slip surface, appropriately increasing diameter and prestress to enhance both shear performance and radial support resistance. The research findings provide a reference for calculating the shear performance of full-length prestressed bolts.

Keywords: soft rock tunnel; shear slip theory; shotcrete-bolt support; neutral point; support resistance

1. Shear Slip Failure Theory and Practical Analysis

During tunnel construction, phenomena such as local spalling of shotcrete, bending of steel arches, and cracking of secondary linings frequently occur, characterized by large deformation magnitudes and rapid deformation rates. The key to addressing tunnel deformation lies in analyzing the mechanical effects of support structures and identifying the root causes of their failure, thereby enabling the design of more effective support methods. Scholars have employed numerical analysis to illustrate the mechanical mechanisms of support systems [1-3], while others have measured the internal force variation characteristics and failure mechanisms of soft rock tunnel support components through testing and monitoring [4-6].

Liu et al. [7] proposed the shear slip theory, which can be applied to tunnel deformation stability analysis and support structure strength evaluation. Current research on shear slip theory is extensive. Xiao et al. [8] developed a formula for calculating the active earth pressure beneath composite soil layers during shield tunnel excavation based on shear slip theory. Wang et al. [9] derived expressions for horizontal fracture depth and plastic shear slip lines in circular tunnels under non-associated flow rules for cases where the lateral pressure coefficient $\lambda = 1$ and $\lambda \neq 1$. Guo et al. [10] applied shear slip theory to high-stress tunnels, proposing that the shear slip failure mode in such conditions comprises bedding shear, bedding tension, and rock shear. These studies, based on shear slip line theory, have discussed calculation methods for support resistance, failure modes of surrounding rock, and fracture depths, yielding significant contributions to tunnel support structure stability research. However, their practical engineering application remains somewhat limited.

Regarding research on fully bonded bolts, Freeman [11] first analyzed the stress distribution in fully bonded rock bolts and proposed the neutral point theory, where bolt axial force reaches its maximum while shear stress equals zero at the neutral point. Subsequently, Wang [12] investigated fully grouted bolts, presenting calculation methods for the neutral point and bolt axial force. Yao et al. [13], based on neutral point theory, treated bolt axial force as a concentrated force and derived the shear stress distribution along the bolt using Mindlin's solution, obtaining integral expressions for axial force distribution in fully bonded bolts between the near end-neutral point and neutral point-far end segments. Notably, research on fully bonded bolts typically neglects transverse shear effects, treating bolts as purely tension members. This "tie-rod model" is suitable for intact rock masses without joints. For jointed rock masses, however, deformation characteristics and mechanical properties are significantly influenced by discontinuities, rendering the "tie-rod model" inadequate. In unstable rock masses reinforced with bolts, the bolt shank provides strong lateral constraint, and sufficient shear stiffness can prevent rock mass sliding along structural planes. Therefore, both axial tension and transverse shear effects must be considered when evaluating bolt reinforcement capacity.

Current research on shear slip theory primarily focuses on slip body failure mechanisms and verification of support structure resistance adequacy, with limited investigation into shear performance when designing full-length prestressed bolts using this theory. To study the shear performance of full-length prestressed bolts and determine their action mechanism, this research establishes the applicable range of internal friction angles for slip line equations based on shear slip failure theory and neutral point theory. Calculation formulas for the neutral point and support force of full-length prestressed bolts considering shear performance are proposed, factors influencing the neutral point of prestressed bolts and the impact of neutral point variation on support performance are analyzed, and the methodology is applied to a deep-buried tunnel engineering case to provide reference for similar calculations.

1. Shear Slip Failure Theory and Practical Analysis

After circular tunnel excavation, when vertical stress is the maximum principal stress, shear slip surfaces form on both sides of the tunnel at an angle of $\alpha = \pi/4 - \phi/2$ to the principal stress trajectories (where α is the initial shear slip fracture angle and ϕ is the internal friction angle), ultimately generating shear slip bodies on both sides as shown in [Figure 1: see original paper]. When horizontal stress is the maximum principal stress, shear slip bodies form on the top and bottom of the tunnel. This study assumes vertical stress as the maximum principal condition.

The shear slip body is located within the plastic zone, and its equation consists of a pair of logarithmic spirals. The coordinates of points on the slip line (r, θ) can be expressed in polar coordinates as [14]:

$$r = r_0 e^{[(\theta-\alpha)\tan\alpha]}$$

$$b = 2r_0 \cos\alpha$$

where r is the curve radius of curvature, r_0 is the tunnel excavation radius, θ is the polar angle, α is the initial fracture angle, and b is the distance from the shear slip body initiation point to the tunnel center.

The maximum radius of curvature of the slip body is $r = 1.5r_0$ to $1.8r_0$ [14-15]. The applicable range of the shear slip curve equation (1) is calculated here with $\alpha = \pi/4 - \phi/2$, with results presented in .

Based on the determination formula for α and the polar coordinate equation for r, the value of $(\theta - \alpha)\tan\alpha$ should range between 0.4 and 0.6. Through algebraic calculation, $\alpha \in (17.5^\circ, 30^\circ)$ and $\phi \in (30^\circ, 55^\circ)$, indicating that the slip curve equation is only applicable to rock masses with $\phi = 30^\circ$ to 55°.

An investigation and analysis of deformation and failure characteristics of tunnel support structures under complex geological conditions in China are summarized in . The failure patterns of some tunnel support structures are illustrated in [Figure 2: see original paper].

Analysis of and [Figure 2: see original paper] reveals that regardless of shallow or deep burial, spalling of shotcrete, twisting deformation of steel arches, and cracking of secondary linings are common failure modes. The underlying cause is that after excavation, stress release causes rapid increases in rock deformation rates, and stress differences induce shear slip effects, with only the rock mass itself providing resistance. After initial support installation, full-length prestressed bolts can be considered as suspension members in close contact with the rock mass, providing certain shear capacity together with the rock. Since initial shotcrete and steel arches are located at the rock surface, shear forces at potential slip surfaces deep within the rock mass are entirely borne by bolts and the rock mass. As stress continues to release, excessive stress differences generate shear slip bodies, requiring full-length prestressed bolts to function not only in axial tension but also in shear to prevent sliding along slip surfaces. The shear forces on bolts at slip surfaces are complex and cannot be neglected, necessitating consideration of both axial tension and transverse shear performance in bolt design.

2. Optimized Calculation Method for Minimum Support Resistance

The minimum support resistance $P_{\min}$ is traditionally calculated using the following formula [15,20]:

$$P_{\min} = P_b + P_s$$

where P_b is the support resistance balancing deformation pressure and P_s is the resistance required to support the rock mass self-weight. This conventional method involves cumbersome calculations of plastic zone radius R, in-situ stress P_0, and other parameters. A new simplified calculation method is derived herein.

As shown in the calculation schematic [Figure 3: see original paper], if the shear slip surface area S_{BCD} can be determined, the external forces can be calculated using the failure wedge concept similar to conventional retaining structures. Taking a differential area dA with height approximated as arc length $ds = rd\theta$, the following equation can be established:

$$A = \int r\,ds = \int r^2 d\theta = \frac{1}{4\tan\alpha}\left[e^{(\pi-2\alpha)\tan\alpha} - 1\right] r_0^2 = k_0 r_0^2$$

where A is the area of figure BCO and k_0 is an approximate coefficient, with other symbols as previously defined.

Given that $\alpha \in (17.5^\circ, 30^\circ)$, substituting α into equation (4) yields k_0 values presented in . The results show that when $\alpha \in (17.5^\circ, 30^\circ)$, k_0 varies between 0.97 and 1.02, allowing area A to be approximated as the area of a square with side length r_0. The wedge slip surface area on each side can be calculated as:

$$S_{BCD} = 2A - \frac{4 + 2\alpha - \pi}{4} r_0^2$$

Multiplying the wedge slip surface area by the rock mass unit weight γ yields the vertical force per unit length. Multiplying further by the horizontal force coefficient k specified in Table D.0.1 of the *Code for Design of Railway Tunnels* (TB 10003—2016) [21] gives the required minimum support resistance $P_{\min}$:

$$P_{\min} = k \cdot S \cdot \gamma$$

Comparison of the two methods reveals: (1) The new method requires only basic parameters such as rock mass classification, internal friction angle, and tunnel radius, significantly reducing computational effort; (2) Example calculations show results from both methods are very close, with the new method yielding slightly higher values, which provides greater safety margins for support structure design.

3. Mechanical Analysis of Full-Length Prestressed Bolts in Shotcrete-Bolt Support

The mechanical behavior of shotcrete-bolt support systems is complex, with total support resistance comprising contributions from shotcrete, steel arches, rock mass, and bolts. The force relationship between the shear slip body and support system is illustrated in [Figure 4: see original paper]. Specific calculation methods for shotcrete, steel arch, and rock mass resistance are detailed in reference [14].

3.1 Neutral Point Analysis of Full-Length Prestressed Bolts Before calculating bolt forces, preliminary design of bolt length and diameter should be performed. Neutral point calculations for bolts with and without prestress are compared below.

1) Without prestress, the neutral point is calculated as:

$$\rho = \frac{r_0 + l}{e^{\psi}}$$

where ρ is the neutral point position, l is bolt length, B is a coefficient with different expressions for different zones (plastic zone B_1 and elastic-plastic zone B_2 as described in reference [12]), and R is the plastic zone radius.

2) With prestress, the initial stress state is shown in [Figure 5: see original paper]. Based on reference [12], the neutral point for fully grouted prestressed bolts is calculated as:

$$\int_{r_0}^{r_0+l} U\tau \, dr = \int_{r_0}^{r_0+l} UK(u_\rho - u_i) \, dr = F$$

where F is the bolt prestress, U is bolt perimeter, u_i is radial rock displacement at any point, and K is the rock shear proportion coefficient (K_1 for plastic zone, K_2 for elastic-plastic zone).

For plastic and elastic-plastic zones, the neutral point expressions are:

Plastic zone:

$$\rho = \frac{r_0 + l}{e^{(F+\psi)/\omega}}$$

Elastic-plastic zone:

$$\rho = \frac{r_0 + l}{e^{(F+\psi+\phi)/\omega}}$$

where $\omega = UK_1B_1(R - r_0) + UK_2B_2(r_0 + l - R)$ and $\psi = UK_1B_1 \ln(R/r_0) + UK_2B_2 \ln[(r_0+l)/R]$. Since K, B, R, and r_0 are constants in equations (12), and ω and ψ become constant once bolt length l and diameter d are determined, ρ is inversely proportional to F. Similarly, ρ is directly proportional to d. Analysis of neutral point formulas reveals: (1) With prestress, increasing prestress F moves the neutral point toward the bolt head (inversely proportional); (2) Without prestress, neutral point position is independent of bolt diameter, while with prestress, increasing diameter d moves the neutral point toward the bolt tail (directly proportional), and decreasing diameter moves it toward the head.

3.2 Bolt Axial Force Calculation The bolt axial force N at any shear slip surface r is:

$$N = \int \tau U \, dx + F = \int_{r_0}^{r} UK(u_r - u_{r_0}) \, U \, dx + F$$

3.3 Support Resistance Provided by Bolts The support resistance P' provided by bolts is:

$$P' = \frac{N \cos\alpha}{e \cdot t \cos\alpha - \cos\theta_0}$$

where e and t are longitudinal and transverse bolt spacing, respectively, and N is bolt axial force. Since only bolts within the α to θ_0 angle range contribute resistance to the slip body, and P_m is a concentrated force, it is assumed to be uniformly distributed over the shear zone height $b/2$:

$$P' = \frac{mr_0(\cos\alpha - \cos\theta)}{b/2}$$

Analysis of equations (10)-(15) shows that full-length prestressed bolt support resistance is influenced by neutral point position. Two scenarios are discussed: First, increasing bolt diameter shifts the neutral point toward the bolt tail, proportionally increasing both axial force and support resistance according to equations (13) and (15); conversely, decreasing diameter reduces both values. Second, increasing prestress shifts the neutral point toward the bolt head but still increases axial force and support resistance proportionally; decreasing prestress reduces both. Therefore, increasing either bolt diameter or prestress within specified ranges enhances bolt support resistance. The recommended bolt diameter range is 20-28 mm, with initial prestress recommended at 0.5-0.8 times the tensile design value [22], not exceeding the bolt's tensile yield limit, while satisfying $\rho \geq r_0$.

3.4 Bolt Shear Force Calculation Shear slip bodies undergo relative displacement with the rock mass. At slip surfaces, bolts experience both axial and shear forces, with deformation shown in [Figure 6: see original paper]. The bolt shear force T comprises the shear component from axial force N and the direct shear Q on the shear plane [23]:

$$T = N(\sin\beta\tan\phi + \cos\beta) + Q(\sin\beta - \cos\beta\tan\phi)$$

where Q is the shear force on the plane:

$$Q = \frac{N^2}{2\sqrt{(380 \times 360)^2 - N^2}}$$

and β is the acute angle between the bolt axis and slip surface, which can be considered as $\beta = \pi/2 - \alpha$ according to shear slip theory. After calculating axial force N and shear force Q at the slip surface, the bolt shear force can be determined. The shear stress at any point on the bolt cross-section can then be calculated using the shear stress reciprocity theorem:

$$\tau_m = \frac{4T}{\pi d^2}$$

where τ_m is the shear stress on the bolt cross-section and A_m is the cross-sectional area. Finally, the calculated tensile stress is compared with bolt tensile strength, tensile force with pullout resistance, and shear stress with bolt shear strength to verify support adequacy.

4. Case Study

The Youfangping tunnel has a radius of 5 m, Class IV surrounding rock with cohesion $c = 0.32$ MPa, internal friction angle $\phi = 40°$, density $\rho = 2.2$ g/cm^3, Poisson's ratio $\mu = 0.35$, bolts located in the plastic zone with $K = 5$ GPa, and maximum burial depth of 120 m. The tunnel support configuration is detailed in .

During tunnel excavation, large rock deformation occurred with sidewall bulging, longitudinal tensile cracks in the lining, and shotcrete failure, as shown in [Figure 7: see original paper] [20]. A failure cause analysis is presented below.

4.1 Minimum Support Resistance Required for Slip Body P_{min} Given $\phi = 40°$ and $r_0 = 5$ m, $\alpha = 25°$ and $b = 9.06$ m are calculated. Using the traditional method:

$$P_{\text{min}} = P_b + P_0 = 0.745 + 0.648 = 1.393\,\text{MPa}$$

For this Class IV rock mass, the most unfavorable coefficient $k = 0.3$ [23] is selected. The slip body area is calculated as 21.65 m^2, yielding:

$$P_{\min} = 0.3 \times 21.65 \times 2.2 = 1.429\,\mathrm{MPa}$$

4.2 Support Structure Resistance P With calculated average slip surface inclination $\Psi = 23^\circ$ and bolt tension $N = 104.8$ kN, the support resistance provided by initial support and rock mass is summarized in . The total support resistance $P = 1.971$ MPa exceeds the required $P_{\min} = 1.429$ MPa, indicating that the original support design theoretically met requirements. However, since initial support failure occurred, deeper investigation into other failure causes is warranted.

4.3 Bolt Shear Strength Verification Given $\beta = \pi/2 - \alpha = 65^\circ$, $\phi = 40^\circ$, and $N = 104.8$ kN, the shear force is calculated as:

$$Q = \frac{(380 \times 360)^2 - 104.8^2}{2} = 44\,\mathrm{kN}$$

$$T = 104.8(\sin 65^\circ \tan 40^\circ + \cos 65^\circ) + 44(\sin 65^\circ - \cos 65^\circ \tan 40^\circ) = 148.2\,\mathrm{kN}$$

The resulting stresses are:

$$\tau_m = \frac{4 \times 148.2}{3.14 \times 0.022^2} = 390.1\,\mathrm{MPa}$$

$$\sigma_m = \frac{4 \times 104.8}{3.14 \times 0.022^2} = 275.8\,\mathrm{MPa}$$

Experimental studies by Azuar et al. [24-25] indicate that bolt shear strength at joints can reach up to 80% of ultimate tensile strength, giving $\sigma_t = 400$ MPa and $\tau_t = 320$ MPa. Since $\tau_m = 390.1$ MPa $> \tau_t = 320$ MPa while $\sigma_m = 275.8$ MPa $< \sigma_t = 400$ MPa, the bolt shear stress exceeds the steel shear strength, indicating shear failure.

4.4 Comparative Analysis A comparison with literature results and failure cause analysis is presented in . The proposed method (Method) involves fewer parameters and simpler steps, with results differing by only 2.5% from traditional methods while providing higher safety margins. Previous analysis [20] attributed failure to construction disturbance without further mechanical investigation, whereas this study identifies insufficient bolt shear capacity as a deeper root cause.

4.5 Optimization Increasing bolt diameter to 25 mm yields:

$$\tau_m = \frac{4 \times 148.2}{3.14 \times 0.025^2} = 302.1\,\text{MPa} < \tau_t = 320\,\text{MPa}$$

This simple modification reduces shear stress to 302.1 MPa, increasing shear capacity by 22.6% and meeting requirements.

5. Conclusions

1) To satisfy the maximum slip body curvature radius $r = 1.5r_0$ to $1.8r_0$, α should range between 17.5° and 30°, corresponding to $\phi = 30°$ to 55° for applicable rock masses.
2) Addressing the lack of shear performance consideration in bolt design using shear slip theory, this study proposes a calculation method for full-length prestressed bolt support force that incorporates shear performance. Bolt shear at slip surfaces is determined from slip forces and bolt axial force, with shear stress calculated using the shear stress reciprocity theorem and compared against bolt shear strength for design verification.
3) The minimum support resistance can be obtained by multiplying slip body area by rock unit weight γ and the horizontal force coefficient k. This approach eliminates calculations of in-situ stress and loosened zone radius, significantly reducing computational effort compared to traditional methods based on deformation pressure and rock self-weight.
4) Full-length prestressed bolt support performance is affected by neutral point position in two ways: increasing diameter shifts the neutral point toward the bolt tail and proportionally increases axial force and support resistance; increasing prestress shifts the neutral point toward the bolt head but also proportionally increases axial force and support resistance. Both parameters enhance support resistance within specified ranges.
5) Case analysis demonstrates that in shotcrete-bolt support systems, bolts provide minimal support resistance. Designing bolt diameter based solely on total required resistance cannot ensure adequate shear performance. It is recommended to design bolt parameters based on shear values at slip surfaces through an iterative process: initial parameter selection → shear stress verification → parameter modification until slip surface shear stress is less than bolt shear strength.

References

[1] ZUO Shuangying, FU Li, LI Haoyi, et al. Numerical simulation of shotcrete-anchor support for duplex arch tunnel in soft rock based on shear-slip line theory[J]. Hazard control in tunnelling and underground engineering, 2020, 2(4): 44-51.

[2] BOBRYAKOV A P, REVUZHENKO A F. Experimental simulation of spiral slip lines on granular materials[J]. Journal of mining science, 2009, 45(2): 99-104.

[3] GAO S M, CHEN J P, ZUO C Q, et al. Structure optimization for the support system in soft rock tunnel based on numerical analysis and field monitoring[J]. Geotechnical and geological engineering, 2016, 34(4): 1089-1099.

[4] CHEN Hongjun, LIU Xinrong, DU Libing, et al. Sliding failure mechanism and its criterion of unsymmetrical loading shallow buried tunnel in layered rock mass[J]. Chinese journal of underground space and engineering, 2021, 17(6): 1733-1741.

[5] LIU X L, SUN F Y, KONG F L, et al. Experimental investigation on mechanical behavior of anchor and shotcrete support system under axial pull-out action[J]. Geotechnical and geological engineering, 2022, 40(1): 383-393.

[6] GONG C Y, HE X Y, LI Y W, et al. Long-term field corrosion monitoring in supporting structures of China Xiamen Xiangan Subsea Tunnel[J]. Acta metallurgica Sinica (English letters), 2017, 30(4): 399-408.

[7] LIU W P, WAN S F, FU M F. Limit support pressure on tunnel face at different construction line slopes by slip line method[J]. Tunnelling and underground space technology, 2020, 106: 103619.

[8] XIAO Mingqing, FENG Kun, LI Ce, et al. A method for calculating the surrounding rock pressure of shield tunnels in compound strata[J]. Chinese journal of rock mechanics and engineering, 2019, 38(9): 1836-1847.

[9] WANG Yongfu, WANG Cheng, TANG Xiaosong. Slip line solution for circular tunnels based on the non-associated flow rule[J]. Applied mathematics and mechanics, 2013, 34(12): 1285-1290.

[10] GUO Xiaolong, TAN Zhongsheng, LI Lei, et al. Deformation and failure mechanism of layered soft rock tunnel under high stress[J]. China civil engineering journal, 2017, 50(S2): 38-44.

[11] FREEMAN T J. The behaviour of fully-bonded rock bolts in the Kielder experimental tunnel[J]. Tunnels & tunnelling international, 1978, 10(5): 37-40.

[12] WANG Mingshu. Mechanism of full-column rock bolt[J]. Journal of China Coal Society, 1983(1): 40-47.

[13] YAO Xianchun, LI Ning, CHEN Yunsheng. Theoretical solution for shear stresses on interface of fully grouted bolt in tunnels[J]. Chinese journal of rock mechanics and engineering, 2005, 24(13): 2272-2276.

[14] ZHU Yongquan, SONG Yuxiang. Tunnel engineering[M]. Beijing: China Railway Publishing House, 2020.

[15] LIU Qiang. Study on causes and control technology of large deformation in extruded carbonaceous phyllite tunnel of Xiangyu Railway Second Line[D].

Shijiazhuang: Shijiazhuang Tiedao University, 2017.

[16] XIE Yunpeng, CHEN Qiunan, WANG Xiangguo, et al. Study on mechanical characteristics of improved shallow tunnel supporting structure based on Yamamoto method[J]. Chinese journal of applied mechanics, 2023, 40(5): 1096-1105.

[17] CHEN Ziquan, HE Chuan, WU Di, et al. Study of large deformation classification criterion for layered soft rock tunnels under high geostress[J]. Journal of Southwest Jiaotong University, 2018, 53(6): 1237-1244.

[18] ZHONG Youjiang, LIU Shijie, WU Jianhe. Application of double primary support to high geostress soft rock section of Yuntunbao tunnel[J]. Tunnel construction, 2020, 40(1): 90-98.

[19] GUO Shangkun. Study on large deformation mechanism and countermeasures of deep-buried old loess tunnel[D]. Chengdu: Southwest Jiaotong University, 2017.

[20] TAN Xiankun, ZUO Changqun, LIU Daiguo, et al. Analysis of bolt and shotcrete support in soft large-deformation tunnel[J]. Science technology and engineering, 2015, 35(8): 228-232.

[21] National Railway Administration of the People's Republic of China. Code for design of railway tunnels: TB 10003—2016[S]. Beijing: China Railway Publishing House, 2016.

[22] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Technical code for ground anchor and shotcrete support: GB 50086—2015[S]. Beijing: China Planning Press, 2015.

[23] LIU Caihua, LI Yuzong. Research progress in bolting mechanism and theories of fully grouted bolts in jointed rock masses[J]. Chinese journal of rock mechanics and engineering, 2018, 37(8): 1856-1872.

[24] AZUAR J J. Stabilization of fissured rock masses by grouted steel bars[J]. Transport and Road Research Laboratory, 1977(73): 56-62.

[25] AZUAR M M, REUILLE D, HABIB, et al. Rock mass reinforcement by passive rebars[C]//4th ISRM Congress. Richardson, Texas, USA: OnePetro, 1979: ISRM-4CONGRESS-1979-003.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.