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Original scientific paper

Mechanical Model and Parameter Optimization of Bolt-Shotcrete Support on Non-Straight Wall Part of Roadway

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Abstract: The bolt-shotcrete support of roadway is generally calculated by beam model, but the mechanical state of bolt-shotcrete support on the curved side of the roadway is obviously different from that on the straight side. The force of the shotcrete layer is analyzed in order to reasonably determine the bolt-shotcrete support parameters of the curved side of the roadway. The bolt-shotcrete support structure is simplified as a mechanical model of coupling between a fixed-end beam and a cylinder. This study undertakes a stress analysis of a shotcrete layer in order to find the mechanical mechanism of bolt-shotcrete support in a circular roadway (or the arc part of the roadway), and reasonably determine the parameters of bolt-shotcrete support. The bolt-shotcrete supporting structure is simplified as a mechanical model of the coupling between a fixed-end beam and a cylinder. The mechanical model for the influence of shotcrete layer thickness, shotcrete strength, bolt spacing and bolt length on the self-supporting capacity of the surrounding rock is established in combination with the Mohr-Coulomb strength theory. The influential law of the parameters of bolt-shotcrete support and the self-supporting capacity of the surrounding rock is determined. The results show the existence of a linear relationship between the strength of the shotcrete and the self-supporting capacity of the surrounding rock. A quadratic function relationship between the thickness of shotcrete and the self-supporting capacity of the surrounding rock is found. The results also show a cubic function relationship between the spacing and length of the bolt and the self-supporting capacity of the surrounding rock. The research results have a certain guiding significance for the determination of bolt-shotcrete support parameters on the curved side of roadway.

Keywords: bolt-shotcrete support; cylinder; mechanical model

1 INTRODUCTION

Bolt-shotcrete support technology is widely used in underground projects [1-6] such as in mines, tunnels, subways, and so on. Bolt-shotcrete support can maintain the integrity and stability of the surrounding rock to the maximum extent, providing full play to the supporting role of the surrounding rock. It plays an important role in controlling the deformation, displacement, and fracture development of the surrounding rock [7-10].

Several researchers inland and abroad have studied the bolt-shotcrete support technology. Li et al. [11] determined the position of the neutral layer when the shotcrete layer was destroyed and explored the relationship between the bolt-shotcrete support parameters and the self-supporting capacity of the surrounding rock under different support methods. The mechanical model between the self-supporting capacity of the roadway's surrounding rock and the bolt spacing, the shotcrete thickness and the shotcrete strength was established.

Wen et al. [12] established the mechanical model of the composite arch which is composed of the external arch supported by the system bolt, the supporting inner arch of the shotcrete layer, and the steel frame.

The study by Wang et al. [4] was based on the stress analysis of the surrounding rock and shotcrete layer of the roadway. The mechanical model showing the influence of the thickness of the shotcrete layer, the shotcrete strength and the bolt spacing on the self-supporting capacity of the surrounding rock was established.

Fang et al. [13] designed the high pre-stress strong bolt-shotcrete support scheme and used the vibrating string shotcrete stress meter to monitor the stress state of the shotcrete layer after the scheme was implemented underground.

Lyu et al. [14] proposed a 2D semi-model of full-face anchorage of thick soft rock roadway and established a theoretical model of the surrounding rock and anchoring system. The distribution law of stress release, anchor rod and surrounding rock coupling was obtained. Jing et al. [15] studied the mechanical properties of a pre-stressed concrete lining structure and established the calculation models of infinite and semi-infinite length structures. The maximum stress influence range of the pre-stressed concrete lining structure was determined. Wang et al. [16] studied the influence and resultant effects of different viscosity coefficients and bolt support parameters on the coupling rheological model of the rock mass. Wang et al. [17] proposed a robust optimal design of tunnel bolt-shotcrete support structure in order to reduce the sensitivity of the support system to the uncertainty of geotechnical parameters. The study established a robust design system of the bolt-shotcrete supporting structure.

Theoretical calculation is an important method to study the force of structure [18-19]. Previous studies measured or theoretically calculated the shotcrete of the curved side of the roadway (which is located below the bolt-shotcrete support, the spray layer refers to the curved side of the roadway) by simplifying it as a fixed-end beam model. These studies had not considered the supporting effect of the shotcrete layer. This study simplifies the bolt-shotcrete support structure as a straight beam model and a cylinder model. The mechanism for interaction between shotcrete thickness, strength, bolt spacing, bolt length and the surrounding rock self-supporting capacity in bolt-shotcrete support parameters is studied. There is a function relationship between the strength and thickness of shotcrete, the spacing and length of the anchor rod and the self-supporting capacity of the surrounding rock. This has a certain guiding significance for the design and optimization of bolt-shotcrete support parameters.

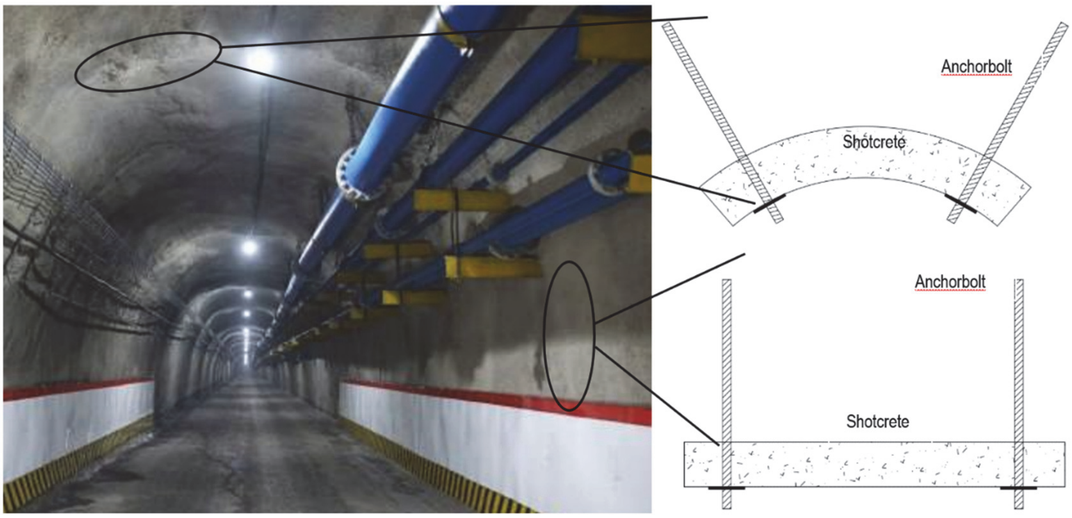
2 ESTABLISHMENT OF THE MECHANICAL MODEl

A bolt-shotcrete support structure refers to the bolt and shotcrete which together produce supporting resistance to the surrounding rock. However, the stress states of the bolt and shotcrete are completely different. The surrounding rock of the roadway converges in a radial direction from the roadway due to the action of ground pressure. The shotcrete layer is subjected to the load imposed by the surrounding rock, which is regarded as a uniform load. The anchor shotcrete structure deforms under the action of the surrounding rock load, and the anchor rod produces the tension. The pressure is generated inside the spray layer to prevent its radial shrinkage.

The study assumes that the shotcrete bearing layer between anchors is a continuous, homogeneous, and isotropic material that meets the assumptions on elasticity, as shown in Fig. 1. Its stress characteristics are shown in Fig. 2.

The pressure of the surrounding rock on the spray layer is shown as q. The supporting force of the anchor rod is F_1. The pressure in the spray layer is F_2. To understand the stress state of the spray layer more intuitively, the surrounding rock pressure, q, is divided into two parts based on bolt suspension theory and coordinated deformation of bolt and spray layer.

The first is the balance with the supporting force of the anchor rod, q_1, which is simplified as the analysis of the fixed-end beam model. The other is the balance with the pressure in the spray layer, q_2 which is analyzed through the cylinder model.



(a) Pictures of field of bolt-shotcrete support (b) Pictures of simpled of bolt-shotcrete support

Figure 1 Pictures of field and simpled of bolt-shotcrete support

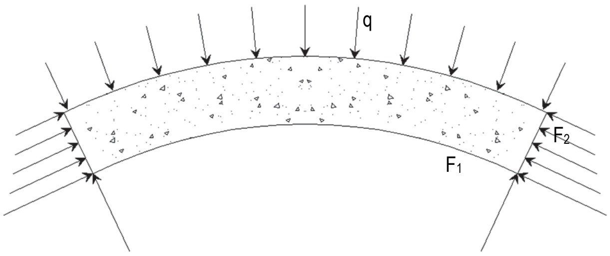


Figure 2 Schematic diagram of bolt-shotcrete supporting structure

If the radial displacement is Δ_1, then the spray layer is produced under the action of the pressure of the surrounding rock. The elongation of the bolt is Δ_1. The strain of the bolt is Δ_1/L_1, and the average strain of the spray layer is Δ_1/R_Z.

$$\begin{cases} F_1 = E_1 \times \dfrac{\Delta_1}{L_1} \times R_1^{\,2} \times 3.14 \\ F_2 = E_2 \times \dfrac{\Delta_1}{R_Z} \times h \times J \end{cases} \tag{1}$$

$$\begin{cases} q_1 = q \times \dfrac{F_1}{F_1 + F_2} \\ q_2 = q \times \dfrac{F_2}{F_1 + F_2} \end{cases} \tag{2}$$

L_1 is the length of the anchor rod. R_z is the radius of the middle layer of the spraying layer. E_1 is the elastic modulus of the anchor rod. R_1 is the radius of the anchor rod. E_2 is the elastic modulus of the spraying layer. h is the thickness of the spraying layer. J is the row spacing of the anchor rod.

2.1 Fixed-End Beam Model

The fixed-end beam model is a simplified model which only considers the action of anchor rod in the bolt-shotcrete structure. The fixed-end beam model establishes the Cartesian coordinate system with the beam center as the origin, as shown in Fig. 3.

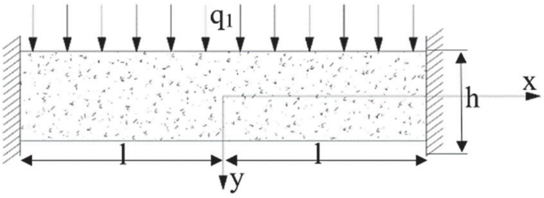


Figure 3 Mechanical model of fixed-end beam of bolt-shotcrete support (excluding self-weight)

The uniform load in Fig. 3 is q_1. The length in x direction is 2l (the bolt spacing L). The length in y direction is h (the spray thickness). The two ends are fixed.

Wang et al. [4] analyzed the mechanical model of statically indeterminate beams with a fixed single span at both ends subjected to uniformly distributed loads in detail. The stress components of statically indeterminate beams with fixed single spans at both ends under uniformly distributed loads (q_1) were obtained.

$$\begin{cases}\sigma_x=\dfrac{2q_1l^2}{h^3}\left(l^2-3x^2\right)y+\dfrac{4q_1}{h^3}y^3-\dfrac{3(2+\mu)q_1}{2h}y-\dfrac{\mu q_1}{2}\\ \sigma_y=-\dfrac{2q_1}{h^3}y^3+\dfrac{3q_1}{2h}y-\dfrac{q_1}{2}\\ \tau_{xy}=\dfrac{6q_1}{h^3}xy^2-\dfrac{3q_1}{2h}x\end{cases}\tag{3}$$

2.2 Cylinder Model

The cylinder model is a part of the mechanical model of the bolt-shotcrete support excluding the action of the bolt. The cylinder model does not consider the influences of the bolt on the shotcrete layer. The stress state of the cylinder model is shown in Fig. 4.

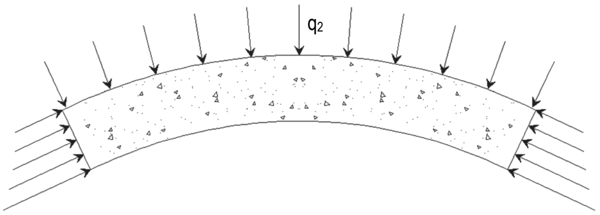


Figure 4 Stress state of cylinder model

The Lame solution of the cylinder subjected to uniformly distributed load in elasticity is taken as the analytical solution of the cylinder model. The Lame solution of the cylinder subjected to uniformly distributed pressure is the analytical solution of the stress state of any point in the cylinder under the condition of uniformly distributed force. Lame's solution is expressed as follows:

$$\begin{cases}\sigma_\rho=-\dfrac{\dfrac{R^2}{\rho^2}-1}{\dfrac{R^2}{r^2}-1}q_1-\dfrac{1-\dfrac{r^2}{\rho^2}}{1-\dfrac{r^2}{R^2}}q_2\\ \sigma_\varphi=\dfrac{\dfrac{R^2}{\rho^2}+1}{\dfrac{R^2}{r^2}-1}q_1-\dfrac{1+\dfrac{r^2}{\rho^2}}{1-\dfrac{r^2}{R^2}}q_2\end{cases}\tag{4}$$

where σ_ρ is the axial stress; σ_φ is the circumferential stress; R is the outer radius of the cylinder; r is the inner radius of the cylinder; q_1 is the internal pressure (different from the uniform load q_1 of the fixed-end beam model); q_2 is the external pressure; ρ is the axial position of the calculated point.

Under the condition of external load only, Lame's solution is simplified as follows:

$$\begin{cases}\sigma_\rho=-\dfrac{1-\dfrac{r^2}{\rho^2}}{1-\dfrac{r^2}{R^2}}q_2\\ \sigma_\varphi=-\dfrac{1+\dfrac{r^2}{\rho^2}}{1-\dfrac{r^2}{R^2}}q_2\end{cases}\tag{5}$$

The negative sign in the formula indicates the compressive stresses, σ_ρ and σ_φ.

2.3 Mechanical Coupling Model

The mechanical model of the bolt-shotcrete supporting structure is a coupling model of the fixed-end beam model considering only the bolt action, and the cylinder model considering only the spraying layer. The cylinder model is solved in polar coordinates, which must be treated in order to be coupled with the fixed-end beam model.

The method of turning the curve into straight is used to deal with the solution of the cylinder model. In the cylinder model σ_ρ and σ_φ are only functions of the variable ρ and do not change along the circumferential direction. When the circumferential and radial directions correspond to the x and y directions respectively, ρ can then be expressed as the mechanical model of $R_{z\text{-}y}$. The mechanical model of the bolt and shotcrete support structure is as follows. The stress relation expressed by known parameters is obtained by substituting Eq. (1) and Eq. (2) for Eq. (6), such as Eq. (7).

$$\begin{cases}\sigma_x=\dfrac{2q_1l^2}{h^3}\left(l^2-3x^2\right)y+\dfrac{4q_1}{h^3}y^3-\dfrac{3(2+\mu)q_1}{2h}y\\ -\dfrac{\mu q_1}{2}-\dfrac{1+\dfrac{r^2}{\left(R_{\mathrm{z}}-y\right)^2}}{1-\dfrac{r^2}{R^2}}q_2\\ \sigma_y=-\dfrac{2q_1}{h^3}y^3+\dfrac{3q_1}{2h}y-\dfrac{q_1}{2}-\dfrac{1-\dfrac{r^2}{\left(R_{\mathrm{z}}-y\right)^2}}{1-\dfrac{r^2}{R^2}}q_2\\ \tau_{xy}=\dfrac{6q_1}{h^3}xy^2-\dfrac{3q_1}{2h}x\end{cases}\tag{6}$$

$$\begin{cases}\sigma_x=\left(\dfrac{2l^2}{h^3}\left(l^2-3x^2\right)y+\dfrac{4}{h^3}y^3-\dfrac{3(2+\mu)}{2h}y-\dfrac{\mu}{2}\right)\cdot\\ \cdot\dfrac{q}{1+\dfrac{E_2hJL_1}{3.14E_1R_1^2R_{\mathrm{z}}}}-\dfrac{1+\dfrac{r^2}{\left(R_{\mathrm{z}}-y\right)^2}}{1-\dfrac{r^2}{R^2}}\cdot\dfrac{q}{1+\dfrac{3.14E_1R_1^2R_{\mathrm{z}}}{E_2hJL_1}}\\ \sigma_y=\left(-\dfrac{2}{h^3}y^3+\dfrac{3}{2h}y-\dfrac{1}{2}\right)\cdot\dfrac{q}{1+\dfrac{E_2hJL_1}{3.14E_1R_1^2R_{\mathrm{z}}}}-\\ -\dfrac{1-\dfrac{r^2}{\left(R_{\mathrm{z}}-y\right)^2}}{1-\dfrac{r^2}{R^2}}q_2\cdot\dfrac{q}{1+\dfrac{3.14E_1R_1^2R_{\mathrm{z}}}{E_2hJL_1}}\\ \tau_{xy}=\left(\dfrac{6}{h^3}xy^2-\dfrac{3}{2h}x\right)\cdot\dfrac{q}{1+\dfrac{E_2hJL_1}{3.14E_1R_1^2R_{\mathrm{z}}}}\end{cases}\tag{7}$$

Parameter values selection (some of which are taken from Wang et al. [4]) is shown in Tab. 1.

Table 1 Model Parameter selection

q / MPa	L_1 / m	r / m	h / m	R_1 / m	L / m	J / m	μ	E_1 / MPa	E_2 / MPa
0.10	2.40	2.50	0.06	0.01	1.20	2.00	0.25	2.00×10^5	7.00×10^3

Theoretically, the dangerous point should be located in the middle of the beam or at the upper and lower end of the beam. The stress of the dangerous point is calculated by incorporating the parameters as shown in Tab. 2.

Table 2 comparison of stress at dangerous points

Position	$x = 0$ $y = 0.03$	$x = 0$ $y = -0.03$	$x = 0.6$ $y = 0.03$	$x = 0.6$ $y = -0.03$
σ_x	−1.28	−1.75	−2.07	−0.96
σ_y	0	−0.04	0	−0.04
τ_{xy}	0	0	0	0

As can be deduced from Tab. 2, the spray layer does not produce tensile stress. The most dangerous point is located at $x = 0.6$, $y = 0.03$.

3 MOHR-COULOMB STRENGTH THEORY

The Mohr-Coulomb strength theory is a classical theory used to describe the strength of a rock under compressive stress [20]. It is considered that the failure caused by compressive stress is actually shear failure and the failure of rock mass is mainly determined by the maximum principal stress and the minimum principal stress (σ_1 and σ_3), but independent of the intermediate principal stress [21-23].

The bolt-shotcrete supporting structure provides vertical stress, σ_3, to change the surrounding rock from two-dimensional stress state to three-dimensional stress state. The stress circle moves to the right with the increase of σ_3. The shear strength of the rock mass increases from τ_1 to τ_2 and the maximum principal stress of the rock mass increases from σ_1 to σ'_1. The stability of the surrounding rock is enhanced. The self-supporting capacity of the surrounding rock is characterized by the maximum principal stress, σ_1. The change of self-supporting capacity of the surrounding rock is reflected by the change of σ_1, as shown in Fig. 5. The failure criterion is described in Eq. (8).

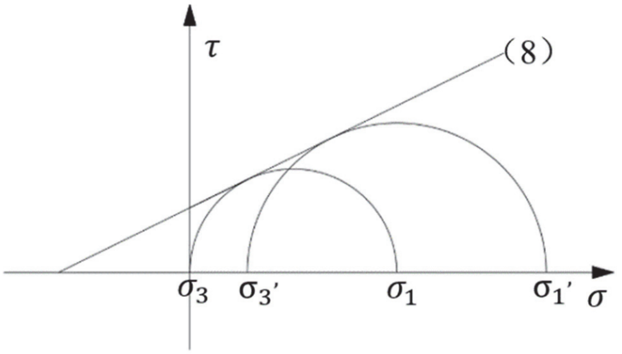


Figure 5 Mohr Coulomb failure criterion

$$\sigma_1 = \frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \frac{2c\cos\varphi}{1-\sin\varphi} \tag{8}$$

4 OPTIMIZATION OF BOLT-SHOTCRETE SUPPORT PARAMETERS

The parameters of bolt-shotcrete support include the length of anchor rod, the anchor rod row spacing, the anchor rod spacing, the strength of shotcrete and the thickness of shotcrete. The essence of bolt-shotcrete support is to improve the self-bearing capacity of surrounding rock. This paper mainly analyzes the influence of anchor rod spacing, anchor rod length, shotcrete thickness and shotcrete strength on the self-bearing capacity of the surrounding rock and establishes the corresponding relationship equations.

σ_3 is the force of bolt-shotcrete support structure on the surrounding rock. It is the reactionary force of the surrounding rock to the bolt-shotcrete support structure, q. σ_3 is equal to q. The surrounding rock consists of sandy mudstone that has a cohesion force of 4.5 MPa and an internal friction angle of 31°. The q in Eq. (7) is substituted for σ_3 in Eq. (8). The relationship between shotcrete thickness (h), shotcrete strength (σ_x), bolt spacing (2l), bolt length (L_1), and the self-supporting capacity of the surrounding rock (σ_1) is obtained.

$$\sigma_1 = \frac{3.124\sigma_x}{\left(-\frac{2l^4}{h^2} - \frac{5.25}{4}\frac{1}{1+\frac{700hL_1}{3.14\left(2.5+\frac{h}{2}\right)}} - \frac{2}{1-\frac{2.5^2}{(2.5+h)^2}\times 1+\frac{3.14\left(2.5+\frac{h}{2}\right)}{700hL_1}}\right)} + 15.91 \tag{9}$$

The corresponding relational images are shown in Figs. 6 to 9.

Fig. 6 shows the relationship between the thickness of the shotcrete and the self-supporting capacity of the surrounding rock. The least square method is used to fit the thickness of the shotcrete and the self-supporting capacity of surrounding rock. Where the quadratic polynomial is used the fitted curve basically coincides with the calculated curve (R^2 approaches 1). There is a quadratic function relationship between the thickness of the shotcrete and the self-supporting capacity of the surrounding rock. The growth rate of the self-supporting capacity of the surrounding rock decreases with increases in the thickness of shotcrete. This study does not account for the peak value range of the shotcrete thickness under the support parameters or under realistic conditions. The shotcrete thickness should be reasonably selected according to the support strength and the deformation condition of the shotcrete layer.

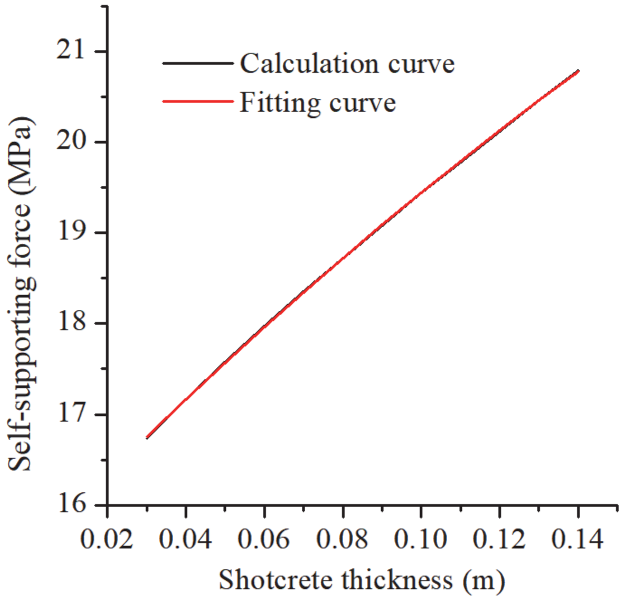


Figure 6 Relationship between shotcrete thickness and self-supporting capacity of surrounding rock

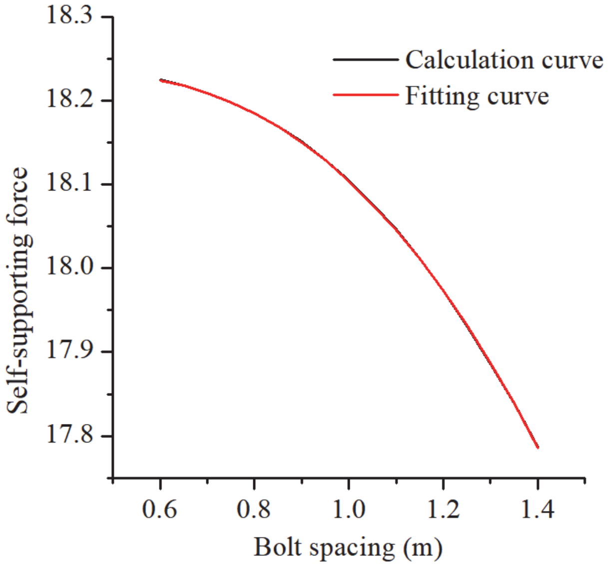


Figure 7 Relationship between bolt spacing and self-supporting capacity of surrounding rock

Fig. 7 shows the relationship between the bolt spacing and the self-supporting capacity of the surrounding rock. The least square method is used to fit the curve of the bolt spacing and the self-supporting capacity of the surrounding rock. The fitted curve basically coincides with the calculated curve (R^2 approaches 1) when the cubic polynomial expression is used. The relationship between the bolt spacing and the self-supporting capacity of the surrounding rock is a cubic function. Reducing the bolt spacing can improve the self-supporting capacity of the surrounding rock. The efficiency of improving the self-supporting capacity of the surrounding rock by reducing the bolt spacing is not optimal when compared with other options to improve the self-supporting capacity of the surrounding rock under the condition of the support parameters expressed in this paper.

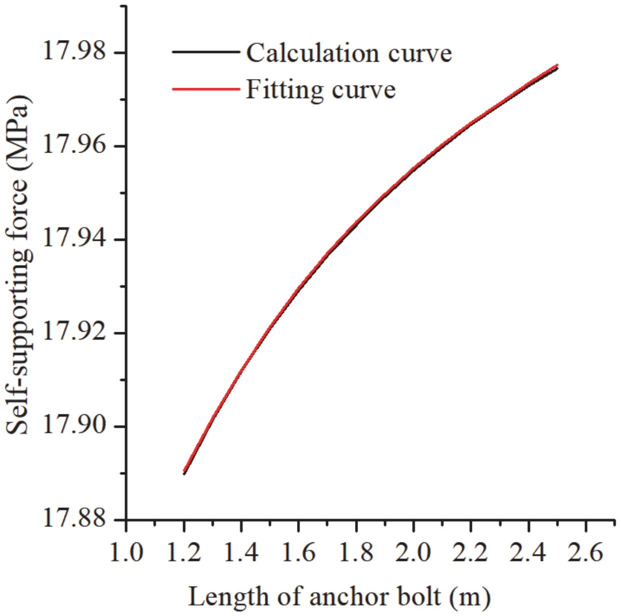


Figure 8 Relationship between bolt length and self-supporting capacity of surrounding rock

Fig. 8 shows the relationship between the length of the anchor rod and the self-supporting capacity of the surrounding rock. The least square method is used to fit the curve of the bolt length and the self-supporting capacity of the surrounding rock. The fitted curve coincides with the calculated curve (R^2 approaches 1) when the cubic polynomial is used. The length of the anchor rod has a cubic function relationship with the self-supporting capacity of the surrounding rock. Reducing the length of bolt can improve the efficiency of the self-supporting capacity of the surrounding rock under the condition of supporting parameters expressed in this paper within a certain range. The length of bolt can meet the design and practical use.

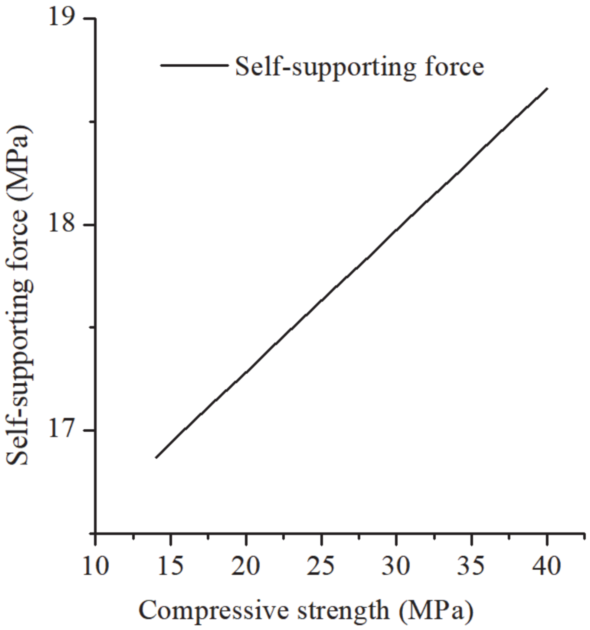


Figure 9 Relationship between shotcrete strength and self-supporting capacity of surrounding rock

Fig. 9 shows the relationship between the compressive strength of shotcrete and the self-supporting capacity of the surrounding rock. According to Eq. (9), there is a first function relationship between the strength of the shotcrete and the self-supporting capacity of the surrounding rock. Increasing the compressive strength of shotcrete can increase the self-supporting capacity of the surrounding rock under the condition of supporting parameters expressed in this paper. However, tensile stress may appear in the shotcrete layer under certain support parameters. The tensile strength of shotcrete is small. The occurrence of tensile stress should be avoided in the design of support parameters.

Amongst the four parameters (bolt spacing, bolt length, shotcrete thickness and strength), the thickness and strength of the shotcrete has obvious influence on the self-supporting capacity of the surrounding rock under the condition of supporting parameters expressed in this paper. When optimizing the parameters, priority should be given to the change in thickness and strength of shotcrete and accordingly adjust the spacing of the anchors.

5 VERIFICATION OF CONCLUSION

The support mode of resin bolt and wet shotcrete is adopted in Guizhou Jinfeng Gold Mine. Wang, S. et al. [4] simplified the shotcrete between bolts to the mechanical model of fixed beam with anchor as fulcrum, established the mechanical model of the influence of shotcrete layer thickness, concrete strength and bolt spacing on the self-supporting capacity of surrounding rock, and explored the influence law of the parameters of shotcreting and bolting support and the self-supporting capacity of surrounding rock. Combined with the on-site construction practice, it is considered that reducing the anchor spacing and increasing the wet spray thickness are reasonable improvement measures. As a result, the bolt-shotcrete support parameters are optimized twice: one is to reduce the bolt spacing, adjust the bolt spacing from 1.2 m to 1.2 m, and adjust the bolt row distance from 2 m to 1.2 m. The other is that the thickness of the spray layer increases from 60 mm to 75 mm. The optimization effect of bolting and shotcreting support parameters is obvious twice, and the total number of roof caving is reduced from 22 times to 5 times per year..

Bolt-shotcrete support is adopted in Chensilou Coal Mine. Xu, Q. et al. [24] use FLAC 3D software to simulate the stress changes of roadway surrounding rock caused by different bolt length and row distance between anchors. The simulation results are as follows: (1) The range of plastic zone of roadway surrounding rock gradually decreases and the anchoring force increases continuously with the increase of bolt length. However, when the bolt length is 3.0 m, the bolt fracture occurs after the surrounding rock deformation is stable. The bolt length is not as long as possible, but has a reasonable value.

(2) The range of plastic zone and deformation of surrounding rock of roadway gradually increase with the increase of the row distance between bolts, and the load borne by a single bolt also increases. The bolts used in roadway support are 20 mm in diameter and 2 m in length, the distance between rows is 0.8 × 0.8 m. The length of bolts is adjusted to 2.5 m, and the distance between rows is adjusted to 0.7 × 0.7 m. After the parameter adjustment, the surrounding rock extrusion zone formed by the bolt is more uniform and the area is larger than that of the original scheme, that is, the range of the extrusion zone is larger, which is more conducive to the stability of the roadway.

6 CONCLUSIONS

(1) Bolt-shotcrete support can be simplified as a coupling mechanical model of fixed-end beam and cylinder. The radial displacement of a roadway is the same in the two models. The uniform load is distributed in proportion to the concentrating force.

(2) The stress calculated by the two models is superimposed. The coupling mechanical model showing the influence of shotcrete thickness, shotcrete strength, bolt spacing and bolt length on the self-supporting capacity of the surrounding rock is derived according to the Mohr-Coulomb failure criterion.

(3) There is a linear relationship between the strength of the shotcrete and the self-supporting capacity of the surrounding rock, and a quadratic function relationship between the thickness of shotcrete and the self-supporting capacity of surrounding rock. There is also a cubic function relationship between the spacing and length of the anchor rod and the self-supporting capacity of the surrounding rock.

(4) According to the existing research, the correctness of the conclusion is verified from three aspects: theoretical analysis, FLAC 3D numerical simulation and field practice.

(5) The support model in this study does not consider the interaction between the roadway axial fixed-end beam model and the roadway circumferential fixed-end beam model. The bolt row spacing can only be used for the force distribution of the two models. There is no optimization of the bolt row spacing.

Acknowledgements

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