

Research Article

Supporting Technology Research in Deep Well Based on Modified Terzaghi Formula

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In order to solve the difficult problem of supporting roadway with large cross section and broken surrounding rock, the large-section inclined shaft of Pingdingshan Coal Mine is taken as the research instance. In this paper, a modified formula for the Terzaghi ultimate bearing capacity of a foundation is established based on rock mass strength criteria. As per the engineering practice, the maximum roof pressure of the inclined shaft is calculated to be 2.7 MPa, and the minimum pressure value from the modified formula is only 0.3 MPa. In order to control the floor heave of the roadway, a U-type steel inverted arch and bolts support scheme was designed. After calculating through the mechanical model of the inverted arch, its bearing capacity is 0.56 Mpa. Through comparison and analysis of various supporting schemes, finally, the “U-type steel + inverted arch + pouring concrete + backwall grouting” technology is selected, and the engineering practice shows that the supporting scheme can effectively improve surrounding rock stability.

1. Introduction

More and more large cross-section roadways need construction in mines in China, due to the need for high efficiency and high yield [1]. The stability control of the surrounding rock of a large-section roadway becomes a difficult problem. With the development of mining engineering to deep wells, many large-deformation phenomena of surrounding rock have appeared. The research shows that the disrepair rate of the roadway with a depth of 1000 meters is about 5 times to 15 times that with the buried depth of 100 meters, and a large-deformation roadway in deep coal mines needs to be renovated 3-4 times a year. And with the increasing number of roadways crossing the gob, the supporting technology has been paid more and more attention by mining scientists. For instance, Lu et al. proposed the asymmetric U-type steel supporting scheme in the roadway with asymmetrical loading, which provides satisfactory supporting effects [2]. Wang et al. established a two-dimensional equation for the force of U-type steel supporting and put forward the concept of the best time for support [3].

For the deep roadway with fracture, it is more susceptible to disturbance stress when critical stability occurs [4]; therefore, many scientists have studied the mechanical properties and failure laws of fractured rock mass. Goodman and Shi innovatively put forward the block theory, and it is considered that key to the stability of surrounding rock is to excavate the key blocks on the surface [5]. The time effect of rock fragmentation is summarized by Tang [6]. Yoshinaka et al. and Anagnostou pointed out that the failure deformation of soft and fractured surrounding rock has rheological properties [7–11]. Joseph proposed the relationship between residual strength and peak strength of cracked rock [12].

From the above research results, some progress has been made in the study of surrounding rock deformation mechanism, fractured surrounding rock characteristics, and supporting technology of large-section fractured surrounding rock, but supporting technology research remains challenging for large-section roadways; in particular, the problem of calculating the roof pressure of broken surrounding rock in deep well is not solved. In this paper, the

large-section inclined shaft of Pingdingshan Coal Mine is taken as the research instance, and a modified formula for the Terzaghi ultimate bearing capacity of a foundation is established based on rock mass strength criteria, by means of mechanical analysis, field monitoring, and numerical simulation; the deformation and failure law of large-section roadways in broken surrounding rock was studied and an effective supporting scheme has been put forward, which has a certain reference to large-section roadway supporting.

2. Engineering Situation

The inclined shaft of Pingdingshan Coal Mine is 1575 m long, and its length in gob is 117 m. The roadway's section is $6.33 \text{ m} \times 4.665 \text{ m}$ (width * height), as shown in Figure 1, and the net sectional area is 23.1 m^2 , so the inclined shaft belongs to a large-section roadway. In order to detect the fracture zone scope of the roadway, the detection recorder YTJ20 is used in the engineering, and the detection results show that the surrounding rock was damaged, as shown in Figure 2. And the mineral composition of surrounding rock was analyzed by X-ray diffraction, and there are a lot of clay minerals, such as kaolinite and montmorillonite in surrounding rock, as shown in Table 1.

3. The Amended Terzaghi Theory Mechanical Model of the Deep Roadway

Engineering practice shows that the lateral pressure coefficient k has great influence on surrounding rock pressure, but the selection of k value is very difficult. In this paper, based on rock mass strength criteria (Mohr-Coulomb criterion and Arnold Verruijt criterion), the lateral pressure coefficient k was calculated by the limit equilibrium method and is shown in Figures 3 and 4.

Through simple mechanical derivation, the following formula can be established:

$$\left. \begin{aligned} \beta &= 90^\circ - \varphi, \\ \tau &= C + k\sigma_v \cdot \tan \varphi, \\ \sigma_v &= k\sigma_v + 2\tau \cdot \tan \beta. \end{aligned} \right\} \quad (1)$$

So, the lateral pressure coefficient k can be calculated by

$$k = \frac{\sigma_v - 2C \cdot \tan \varphi}{\sigma_v (1 + 2 \tan^2 \varphi)} \quad (2)$$

Then, based on the formula for the Terzaghi ultimate bearing capacity of the foundation and the known boundary conditions ($z = 0$ and $\sigma_v = p_0$), the following formula can be established:

$$\begin{aligned} \sigma_v &= \frac{1 + 2 \tan^2 \varphi}{\tan \varphi} \left(\gamma a_1 - C + \frac{2C \cdot \tan^2 \varphi}{1 + 2 \tan^2 \varphi} \right) \\ &\cdot \left(1 - e^{-((\tan \varphi) / (a_1 (1 + 2 \tan^2 \varphi)))z} \right) \\ &+ p_0 \frac{\tan \varphi}{1 + 2 \tan^2 \varphi} e^{-((\tan \varphi) / (a_1 (1 + 2 \tan^2 \varphi)))z}. \end{aligned} \quad (3)$$

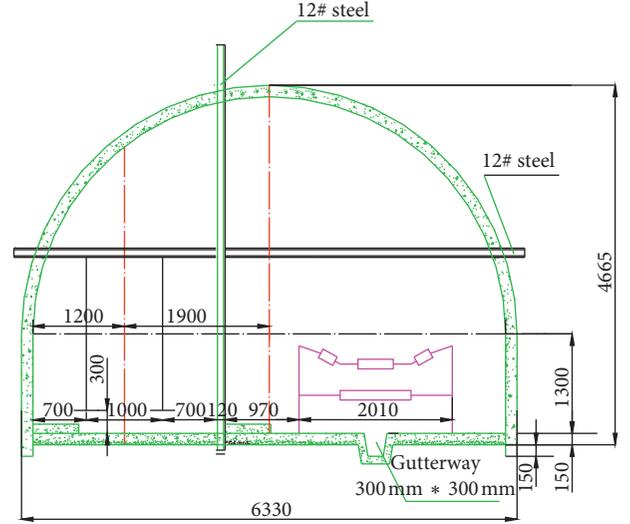


FIGURE 1: Cross section of the roadway.

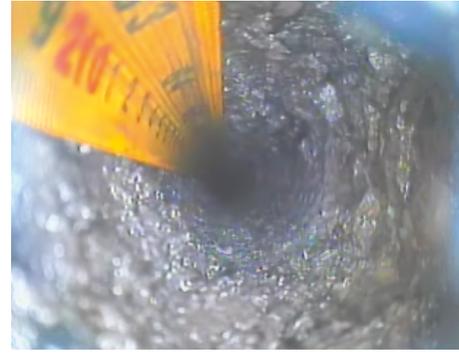


FIGURE 2: Broken surrounding rock.

When the depth of the roadway is greater than $5a$, Equation (3) becomes

$$q = \frac{1 + 2 \tan^2 \varphi}{\tan \varphi} \left(\gamma a_1 - C + \frac{2C \cdot \tan^2 \varphi}{1 + 2 \tan^2 \varphi} \right). \quad (4)$$

In engineering practice, the intermediate principal stress has been proven to exist and has great influence on the roadway's roof pressure. But the intermediate principal stress is not considered in formula (4), so in order to calculate the pressure of the roof more accurately, formula (4) was improved by unified strength theory (UST) in this paper.

When the intermediate principal stress meets the condition that $\sigma_2 \leq ((\sigma_3 + \alpha\sigma_1) / (1 + \alpha))$, the principal stress F can be calculated by the following formula:

$$F = \alpha\sigma_1 - \frac{b\sigma_2 + \sigma_3}{1 + b} = \sigma_r. \quad (5)$$

When the intermediate principal stress meets the condition that $\sigma_2 \geq ((\sigma_3 + \alpha\sigma_1) / (1 + \alpha))$, then the following formula is applied:

$$F = \frac{\alpha}{1 + b} (b\sigma_2 + \sigma_1) - \sigma_3 = \sigma_r, \quad (6)$$

TABLE 1: The mineral ingredient of the inclined shaft.

The mineral ingredient	$\text{Na}_{0.3}\text{Al}_4\text{Si}_6\text{O}_{15}(\text{OH})_6\text{H}_2\text{O}$	SiO_2	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
Proportion (%)	4.5	7.5	79.4	5.2	3.7

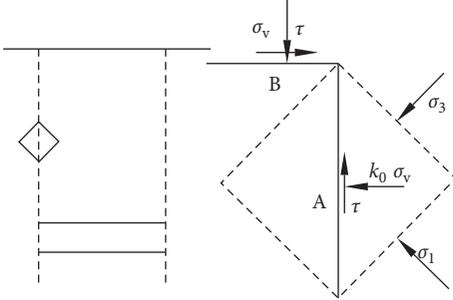


FIGURE 3: The sliding surface under the state of limit equilibrium.

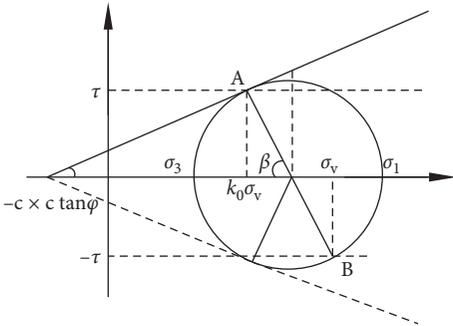


FIGURE 4: Mohr-Coulomb criterion.

where b is a theoretical parameter of UST; σ_τ is the tensile breaking point; and $\sigma_\tau = ((2C \cos \varphi)/(1 + \sin \varphi)) \cdot \alpha$ is the ratio of tension and pressure, in which $\alpha = (\sigma_\tau/\sigma_c) = ((1 - \sin \varphi)/(1 + \sin \varphi))$.

For ease in calculating the intermediate principal stress, the twin shear stress parameter μ_τ is introduced in UST, so the following formula can be obtained:

$$\sigma_2 = \frac{\sigma_1 + \sigma_3}{2} - \frac{(1 - 2\mu_\tau)(\sigma_1 - \sigma_3)}{2} \quad (7)$$

When the twin shear stress parameter meets the condition that $\mu_\tau \leq ((1 - \sin \varphi)/2)$, the following formula can be used:

$$\sigma_1 = \frac{(1 + \sin \varphi)(1 + b - b\mu_\tau)}{(1 + b)(1 - \sin \varphi) - b\mu_\tau(1 + \sin \varphi)} \sigma_3 + \frac{2(1 + b)C \cos \varphi}{(1 + b)(1 - \sin \varphi) - b\mu_\tau(1 + \sin \varphi)} \quad (8)$$

And then formula (8) is converted to $\sigma_1 = ((1 + \sin \varphi_\omega)/(1 - \sin \varphi_\omega))\sigma_3 + ((2C_\omega \cos \varphi_\omega)/(1 - \sin \varphi_\omega))$, in which $\sin \varphi_\omega$ and C_ω can be calculated by the following formula:

$$\left. \begin{aligned} \sin \varphi_\omega &= \frac{(1 + b)\sin \varphi}{1 + b(1 - \mu_\tau) - b\mu_\tau \sin \varphi} \\ C_\omega &= \frac{2(1 + b)C \cos \varphi \cot(45^\circ + (\varphi_\omega/2))}{1 + b(1 - \mu_\tau) - (1 + b + b\mu_\tau)\sin \varphi} \end{aligned} \right\} \quad (9)$$

When the twin shear stress parameter meets the condition that $\mu_\tau \geq ((1 - \sin \varphi)/2)$, then the following formula is applied:

$$\sigma_1 = \frac{(1 + \sin \varphi)(1 + b) - b(1 - \mu_\tau)(1 - \sin \varphi)}{(1 + b\mu_\tau)(1 - \sin \varphi)} \sigma_3 + \frac{2(1 + b)C \cos \varphi}{(1 + b\mu_\tau)(1 - \sin \varphi)} \quad (10)$$

In the same way, $\sin \varphi_\omega$ and C_ω can be calculated by the following formula:

$$\left. \begin{aligned} \sin \varphi_\omega &= \frac{(1 + b)\sin \varphi}{1 + b(1 - \mu_\tau)\sin \varphi - b\mu_\tau} \\ C_\omega &= \frac{(1 + b)C \cos \varphi}{(1 + b\mu_\tau)(1 - \sin \varphi)\tan(45^\circ + (\varphi_\omega/2))} \end{aligned} \right\} \quad (11)$$

The known parameters φ_ω and C_ω are plugged into formula (4), respectively, and then the modified formula for the Terzaghi ultimate bearing capacity of the foundation is obtained:

$$q = \frac{1 + 2 \tan^2 \varphi_\omega}{\tan \varphi_\omega} \left(\gamma a_1 - C_\omega + \frac{2C_\omega \cdot \tan^2 \varphi_\omega}{1 + 2 \tan^2 \varphi_\omega} \right) \quad (12)$$

In order to test the correctness of the modified formula, it is applied to engineering practice in the construction of an inclined shaft in Pingdingshan Coal Mine. The size of the inclined shaft section is 6.33 m * 4.665 m (width * height), the density of surrounding rock $\gamma = 2500 \text{ kg/m}^3$, the uniaxial compressive strength $\sigma_c = 53.18 \text{ MPa}$, the cohesion $C = 0.1 \text{ MPa}$, the internal friction angle $\varphi = 30^\circ$, and the depth of the roadway is 292 m, so it is a deep roadway.

The different twin shear stress parameters (μ_τ) and the UST parameter (b) are plugged into formulas (10) and (11), respectively. φ_ω and C_ω can be calculated and then plugged into formula (12). The roof pressure can be calculated in this way by soft MATLAB.

As shown in Figure 5, when $b = 0.4$, and $\mu_\tau = 0.1$, the maximum roof pressure of the inclined shaft is 2.7 MPa, and the minimum pressure value is only 0.3 MPa; the calculated data are in agreement with those observed in engineering practice.

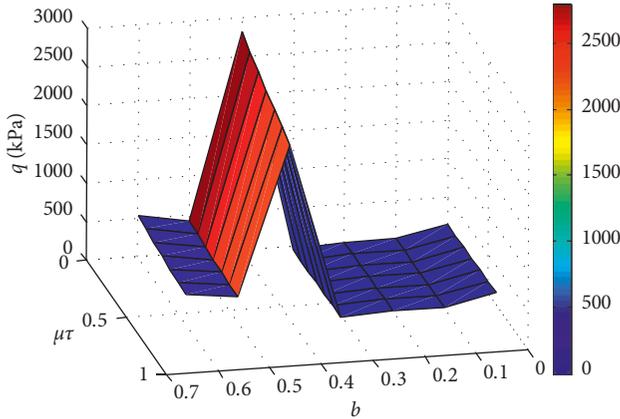


FIGURE 5: Relationship diagram of the roof pressure and UST parameters.

3.1. Stability Analysis of the Inverted Arch. It is easy to cause serious floor heave because of broken surrounding rock. Many engineering practices show that the floor heave can be effectively controlled after bolt support is applied to the roadway bottom and floor. In this paper, the U-type steel inverted arch supplemented by bolts supporting scheme is designed (Figure 6). Therefore, a mechanical model of the inverted arch is determined to calculate its bearing capacity (Figure 7), and the following formula can be obtained from the mechanical equilibrium of the inverted arch:

$$2q_1 + T = P_0 \times L_x \times L_z, \quad (13)$$

where L_z is the width of the inclined shaft along the long-axis direction, $L_z = 0.4$ m; L_x is the width of the roadway, $L_x = 6.33$ m; q_d is the maximum roof pressure of the inclined shaft, as shown in the Section 2, $q_d = 2.7$ MPa; the width of the U-type steel is 0.15 M, so $q_1 = 0.15 * q_d = 0.15 * 2.7$ kN/m; P_0 is the ultimate bearing capacity of the inverted arch; and T is the vertical tension of floor bolting.

In Figures 6 and 7, the bolts' length is 2.4 m, and the diameter is 22 mm, the resistance of each bolt is 200 kN, and so the vertical tension of floor bolting is 600 kN. According to the above known conditions, the bearing capacity of the inverted arch can be calculated by formula (13):

$$P_0 = \frac{2 \times 0.15 \times 2.7 \times 10^3 + 600}{6.33 \times 0.4} = 0.56 \text{ MPa}. \quad (14)$$

From the experience of roadway floor support, the stability of roadway floor rock can be achieved when the reaction force is 0.2 MPa. Therefore, the design of the U-type steel inverted arch supplemented by bolts support is reasonable.

4. Engineering Application

4.1. Support Parameters. After numerical simulation and theoretical analysis, the supporting scheme "U-type steel + inverted arch + pouring concrete + backwall grouting" is applied in Pingdingshan Coal Mine. The support scheme has the following steps: the first step is to lay a metal mesh on the roadway, and the nets' grid is 40×40 mm and the diameter is

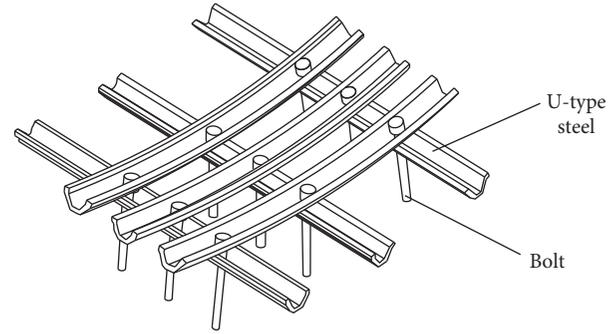


FIGURE 6: U-type steel inverted arch supplemented by bolt, reproduced from Peng et al. [13] (under the Creative Commons Attribution License/public domain).

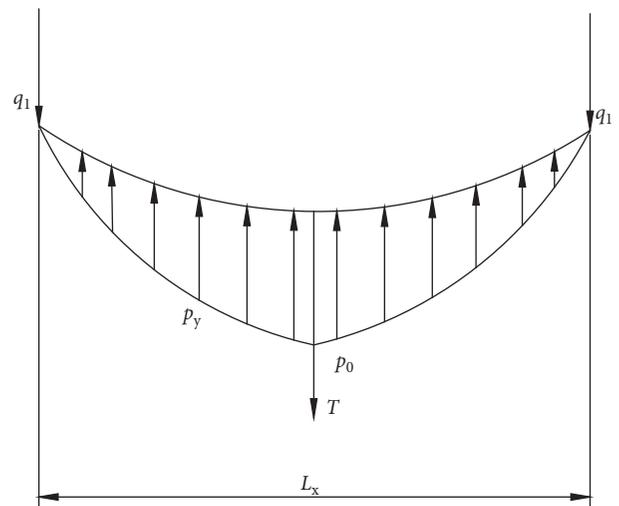


FIGURE 7: The mechanical model of the inverted arch, reproduced from Peng et al. [13] (under the Creative Commons Attribution License/public domain).

4 mm. The second step is to set up U36-type steel support with the inverted arch, the spacing of U36-type steel support is 500 mm, three interlocking beams are set between two adjacent inverted arches, and three bolts are selected to be fastened to the interlocking beams. The third step is to pour intensity of C30 concrete, and the thickness is 500 mm. The fourth step is backwall grouting, and the length of the grouting hole is 4 m. The row and line space of the grouting hole is $2000 \text{ mm} \times 1400 \text{ mm}$. The support parameters are shown in Figure 8.

4.2. Supporting Effect. Field observation is conducted in the inclined shaft, the convergence of two sides is 40 mm, and the convergence between roof and floor is 60 mm, as shown in Figure 9; the deformation rate of roadway surrounding rock tends to be stable in the later period. The roof of the roadway is detected by the detection recorder, as shown in Figure 10, and no large cracks and abscission layers were found in the surrounding rock of the roadway roof. The deformation has been controlled effectively after supporting in Pingdingshan Coal Mine, as shown in Figure 11.

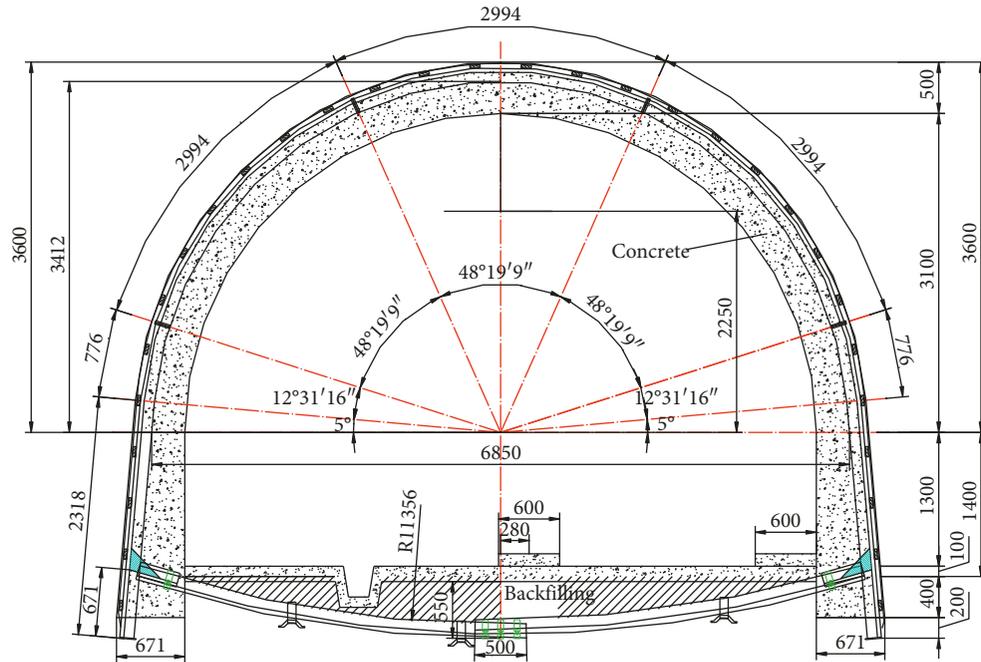


FIGURE 8: Supporting diagram of the inclined shaft in the gob, reproduced from Peng et al. [13] (under the Creative Commons Attribution License/public domain).

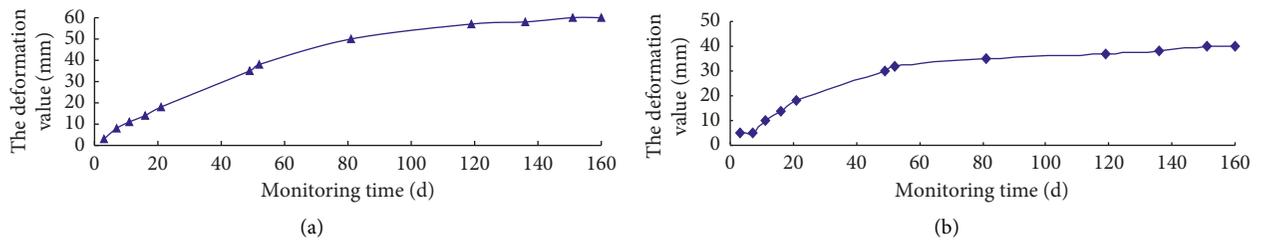


FIGURE 9: Displacement curves of surrounding rock. (a) Convergence between roof and floor. (b) Convergence between two sides.

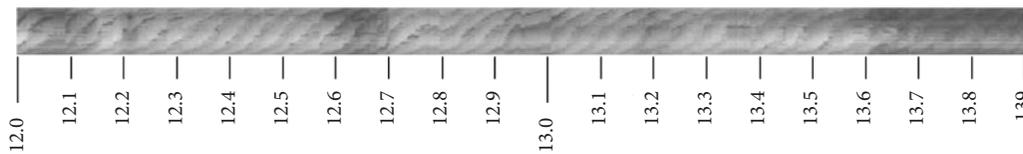


FIGURE 10: The detected map of roof surrounding rock.



FIGURE 11: Supporting effect of the inclined shaft. (a) U-type steel supporting before pouring concrete. (b) Final supporting.

5. Conclusions

- (1) Based on rock mass strength criteria (Mohr–Coulomb criterion and Arnold Verruijt criterion), the lateral pressure coefficient k is calculated by the limit equilibrium method, and the modified formula for the Terzaghi ultimate bearing capacity of a foundation is established; it is applied to the engineering practice of inclined shaft construction in Pingdingshan Coal Mine, the maximum roof pressure of the inclined shaft is 2.7 MPa, and the minimum pressure value is only 0.3 MPa; the calculated results are in agreement with those observed in engineering practice.
- (2) U-type steel inverted arch supplemented by the bolt support scheme was designed to control the floor heave of the inclined shaft. A mechanical model of the inverted arch is established; after calculation, the ultimate bearing capacity of the inverted arch has been achieved as 0.56 Mpa. Hence, the support scheme can effectively control floor heaving.
- (3) A new support technology is designed based on the modified Terzaghi formula in this paper, after the supporting scheme “U-type steel + inverted arch + pouring concrete + backwall grouting” is applied in Pingdingshan Coal Mine; the surrounding rock damage has been controlled effectively, which has a certain reference to large-section roadway supporting.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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