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Research Article

Distribution Law of Deep Complex In Situ Stress and Influence of Underground Engineering in Huanghuai Area

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Huanghuai area is rich in coal resources, but due to the increasingly complex geological environment faced by coal mining, the complexity of structural stress is one of the main problems. In order to find out the distribution law of deep in situ stress in the Huanghuai area, the in situ stress measurement data of 81 effective measuring points in 24 mines with depths ranging from −100 m to −1200 m are analyzed in the present study base on the in situ stress measurement data. Furthermore, numerical simulation and field observation are used to analyze the deformation and failure characteristics of the surrounding rock. The research results show that the deep mining area of Huanghuai exhibited a high stress level, and the vertical and horizontal principal stress increases with increasing depth. The ratio of the lateral pressure coefficient ranges from 0.90 to 2.70, and the in situ stress field presented a trend of transition to the quasihydrostatic pressure field type as the depth extended, in which 80.23% of the measuring points are distributed between 1.20 and 2.10, belonging to the typical tectonic stress field type in which tectonic stress is absolutely dominant. The observation results of the surrounding rock and numerical simulation reveal that when the layout axis of the roadway is approximately perpendicular to the direction of the maximum horizontal principal stress, a high stress concentration area is present on the roof and floor of the roadway, the deformation increases sharply, and the support pressure of the roof and floor increases.

1. Aims and Background

In situ stress data are essential for the prevention and control of disasters, including coal mine development and deployment, roadway layout and support design, coal mining methods and technology selection, mine pressure and rock formation control, and rock burst. As identified by Hast [1], horizontal stress was significantly greater than vertical principal stress, and the horizontal stress changed linearly with the depth. Through theoretical analysis, Mccutchen [2] and Sheory [3] also observed that the horizontal stress in the shallow crust was greater than the vertical stress. Worotniki and Denham [4] established that a linear regression relationship existed between average horizontal stress and vertical stress in Australia in terms of buried depth. With the distribution of buried depth, Brown and Hoek [5] calculated the distribution law of the global measured vertical stress, the horizontal average principal stress, and the vertical stress ratio.

On the basis of the measured data of in situ stress [6, 7], many scholars have conducted research on the deformation and failure mechanism and the effect of control technology of deep coal mine roadways by analysing the distribution law of in situ stress in mining areas [8–10]. Gale investigated the relationship between the stability of the roadway and the direction of in situ stress [11]. Findings were made that, as the maximum horizontal stress direction and the roadway angle increased, the asymmetric deformation and stability of the roadway decreased. In terms of numerical simulation, Cai used the numerical tools of FEM/DEM to simulate the influence of intermediate principal stress on the failure process and strength of excavated boundary rocks [12]. Tang and Hudson developed three-dimensional RFPA software, and conducted a systematic simulation study on the process of rock failure and instability under multiaxial stress conditions [13]. For the exploration of key parameters of bolt support, Doan et al. proposed a support technology combining high prestress bolt support and anchor cable reinforcement [14]. Cai and Kaiser studied the asymmetric failure phenomenon that occurs when a roadway is excavated in the inclined rock layer in the deep high ground stress state and proposed that the key support measures of bolt and anchor cable at the key position of the roadway were prone to large deformation or rock burst disasters [15].

In the present study, the in situ stress data of the deep coal mines in the Huanghuai area in Anhui and Shandong were analyzed, and the distribution characteristics of the in situ stress field in deep mines in the Huanghuai area were investigated. To further analyze the stability effect of local stress distribution on roadway surrounding rocks, the Pansan Coal Mine in Huainan mining area was taken as the starting point. Numerical simulation was used to explore the effect of deep soft rocks roadway support affected by the in situ stress field and optimize the support method. The analysis of the in situ stress distribution law could be used for the surrounding rocks stability evaluation, roadway excavation support design, and other aspects of geological disaster prevention and control.

2. Deformation Characteristics of Deep Buried Roadways

The support system of Xinglong Zhuang Coal Mine of Yankuang Mine in Shandong adopts the combined support of bolts, meshes, and anchors. Through in situ stress testing of Xinglong Zhuang Coal Mine, the angle between the tunneling direction of the transportation roadway in a mining area and the maximum horizontal stress direction is 97°, as shown in Figure 1, which caused the maximum stress concentration to appear at the head of the tunneling. The roof and floor of the roadway are seriously deformed and damaged, and the deformation of the surrounding rocks is difficult to stabilize. The angle between the driving direction of the transportation roadway in the 3303 working face of the third mining area and the measured maximum horizontal principal stress direction is 33°. The skew angle is small, and the surrounding rocks of the roadway are relatively stable. By analysing the fourth and fifth mining areas that have been mined, a similar trend can be found. The angles between the transport roadway driving direction and the maximum horizontal principal stress of the coal mining face in the third and fifth mining areas are found to be generally less than 30°. The horizontal principal stress is almost parallel to roadway driving direction, the horizontal stress had the least influence on the roadway driving, and the angle between the driving direction of the transportation roadway in the fourth mining area and the maximum horizontal principal stress is as high as 82°. Meanwhile, the maximum horizontal principal stress is almost perpendicular the roadway driving direction and has the greatest impact on roadway driving.

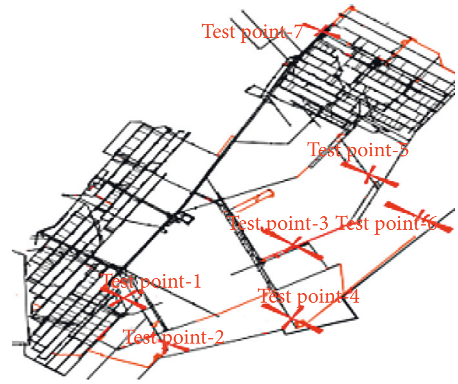


Figure 1: Distribution of in situ stress in Xinglong Zhuang Mine.

As part of the main support system, the Pansan Coal Mine in the Huainan mining area, Anhui province, uses bolt-net-cable combined support. The 1621 (1) face transportation roadway also faces the same support problems of long deformation duration and significantly unstable surrounding rocks. According to the measurement results of the in situ stress of Pansan Coal Mine, the dominant direction of the maximum principal stress of Pansan Coal Mine near the north-south direction and the dominant direction of the minimum horizontal principal stress near the east-west direction, which is consistent with the axial direction of the transportation roadway in the 1621 (1) working face, are shown in Figure 2. The included angle is about 70°, which has a greater impact on roadway excavation, while the horizontal stress concentration is significant with severe roadway roof deformation.

As such, from the observation characteristics of the surrounding rock deformation in the roadway excavation and support engineering practice, the following observations can be made: (1) the surrounding rock deformation in the deep mining areas of Anhui and Shandong is significantly affected by horizontal stress and (2) when the roadway excavation direction is oblique to the maximum horizontal principal stress at a large angle, the roof and floor of the roadway are mainly damaged. In order to further understand the deformation characteristics of the roadway, the distribution of in situ stress and roadway support schemes in Anhui and Shandong mining areas is explored.

3. Distribution Characteristics of Deep In Situ Stress Field

3.1. Methods of Processing Ground Stress Data. Based on the characteristics of roadway deformation in Xinglong Zhuang Coal Mine in Shandong and Pansan Coal Mine in Anhui, statistical analysis was performed on the in situ stress test results of 81 sets of effective measuring points in the range from −100 m to −1200 m in 24 mines in the Huanghuai mining area in the Anhui and Shandong provinces. σ_H is the

(a) (b)

Figure 2: Overview of Pansan Coal Mine Roadway Engineering: (a) distribution of in situ stress in Pansan Coal Mine, Anhui; (b) deformation characteristics of roadway.

maximum horizontal principal stress, σ_h is the minimum horizontal principal stress, and σ_v is the vertical principal stress.

3.2. Variation of Vertical Stress and Horizontal Principal Stress with Buried Depth. The relationship between vertical stress and horizontal stress at each measuring point in the range of −100 m−−1200 m depth in the Huanghuai mining area is shown in Figure 3. Through linear regression analysis of the vertical stress and horizontal stress data, a good linear relationship between the in situ stress distribution and the depth in Huanghuai and other mining areas was found, as shown in Figure 3, and the law of change is

$$\sigma_v = 0.0234H. \tag{1}$$

According to the statistical results, the overlying rock volume in China's mining areas is mostly in the range of 25–33 kN/m^3 with an average bulk density of 27 kN/m^3. The proportional coefficient in (1) reflects the bulk density of the overlying rocks in the Huanghuai mining area. If the average bulk density of the rock mass in the Huanghuai mining area is 23.4 kN/m^3, the vertical stress of the mining area would be roughly equal to the weight of the overlying rocks mass, indicating that the vertical stress of the Huanghuai mining area is mainly composed of the weight of the rock mass. However, the average bulk density of the mining area in China is smaller, and a relationship with the structure is observed, causing several data monitoring points σ_v to fluctuate.

Similarly, as the depth of the measuring point increases, the maximum horizontal stress and the minimum horizontal stress both exhibit an increasing trend. The law of change is

$$\begin{cases} \sigma_H = 0.021H + 3.103, \\ \sigma_h = 0.015H + 0.014, \end{cases} \tag{2}$$

where H is buried depth, the correlation coefficient of σ_H is 0.95, and the correlation coefficient of σ_h is 0.93.

Figure 3 and (2) show that, as the depth increases, σ_H and σ_h increased overall, but the degree of dispersion is larger relative to the vertical stress, and the measurement point data change within the resembling strips of the parallel lines. The linear equation of σ_H and σ_h had a constant value, indicating that there is a certain horizontal stress in the shallow part of the Huanghuai mining area, but as the depth increased, the increase rate of the sum of σ_H and σ_h is less than the bulk density of the rocks. After reaching a certain depth, the relationship of σ_H, σ_v, and σ_h would change, and finally, σ_v would become the maximum stress.

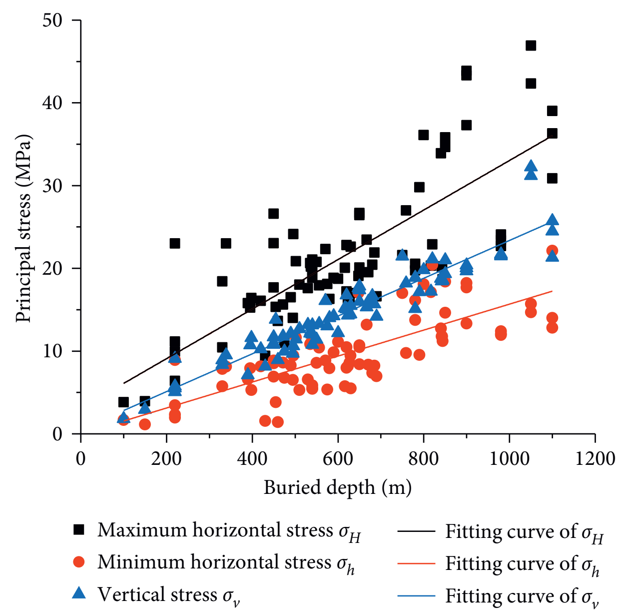


Figure 3: Distribution of ground stress with burial depth.

3.3. Variation of Lateral Pressure Coefficient with Buried Depth. According to statistical analysis, the maximum horizontal principal stress σ_H from −100 m to −1200 m is basically greater than the vertical principal stress σ_v. The data types of several ground stress measurement points belonged to the type $\sigma_H > \sigma_v > \sigma_h$, and only a few measuring points belong to $\sigma_H > \sigma_v > \sigma_h$. As such, the deep in situ stress field in the Huanghuai mining area is found to be dominated by horizontal stress, indicating tectonic stress has an absolute advantage in the in situ stress field. The in situ stress distribution in the Huanghuai mining area is further analyzed from the perspective of the ratio of the maximum horizontal principal stress to the vertical stress, which is the lateral pressure coefficient.

$$\begin{cases} K_{HA} = 0.65 + \dfrac{202.80}{H - 312}, \\ \\ K_{HS} = 1.02 + \dfrac{172.70}{H - 169.30}, \end{cases} \quad (3)$$

where K_{HA} and K_{HS} are the lateral pressure coefficients of the Anhui and Shandong mining areas and the correlation coefficients are 0.87 and 0.84, respectively.

From Figure 4 and (3), observations can be made that the lateral pressure coefficient curves of Shandong and Anhui have the same distribution trend; the distributions of lateral pressure coefficients in the Huanghuai mining area are approximately the same; the lateral pressure coefficients of the Shandong mining area mainly concentrate between 0.90 and 2.70; the lateral pressure coefficient of the Anhui mining area mainly concentrate between 0.80 and 2.30; the measurement points of the two mining areas reach over 90%, of which the lateral pressure coefficient is between 1.20 and 2.10, accounting for 80% of the total, indicating the maximum horizontal principal stress in most areas exceed the maximum vertical stress. The dispersion of the lateral pressure coefficient became smaller as buried depth continues to increase, and the value gradually stabilizes close to 0.95, mainly due to a shallower buried depth of the mine allowing for a greater influence of topography and other factors on the in situ stress, resulting in the horizontal stress in the shallow buried depth area being much larger than the vertical stress, and the data being discrete, the ground stress distribution is stable with deep mining, and the lateral pressure coefficient gradually tends to a fixed value.

4. Analysis of Roadway Instability Mechanism

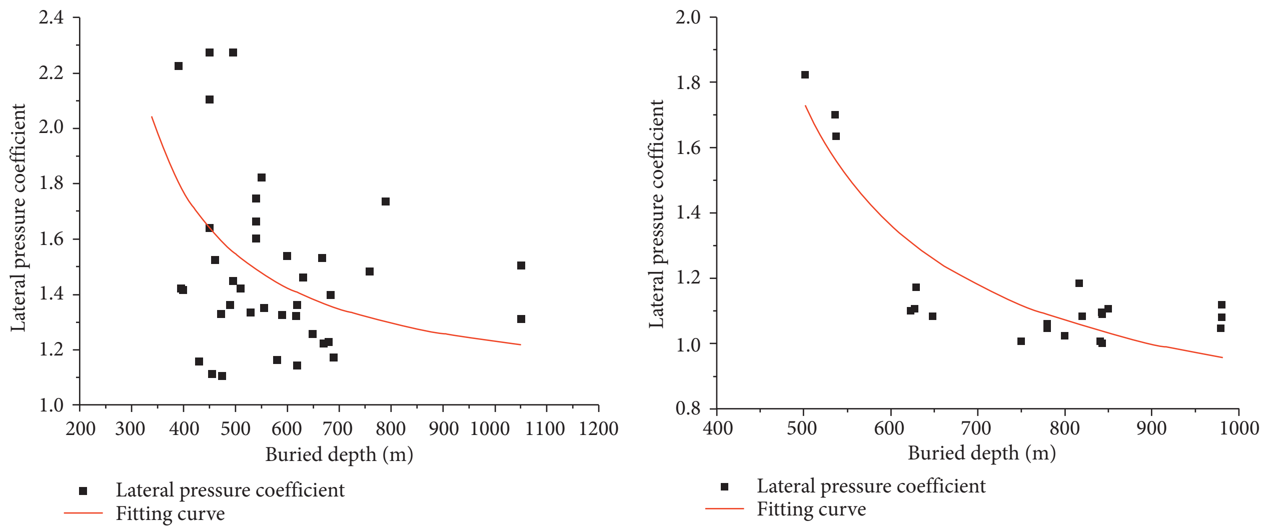
4.1. Analysis of Roadway Instability Based on Geological Causes. Based on the aforementioned research, the Huanghuai deep mining area was dominated by horizontal stress, and the roadway was significantly affected by the horizontal stress during roadway driving. However, most roadways ignore the impact of horizontal stress when designing support, which leads to deviations. Taking the 1621 (1) working face transportation roadway of Pansan Coal Mine in the Huainan mining area as the research object, the geological factors was analyzed in the present study.

During the long-term evolution of the tectonic stress field in the Huainan mining area, the current Huainan mining area basically inherits the characteristics of the tectonic stress field during the Himalayan period. The characteristics of the tectonic stress field during the Yanshan Movement period were retained, and the direction of the maximum principal stress is NW-SE. Here, the major reverse faults in the Pansan Coal Mine are basically in the east-west direction, and the measured maximum horizontal in situ stress is basically in the north south direction. The horizontal compression in the mining area resulted in strong rock formations and well-developed joints, which tended to occur in the north-south X conjugate shear weak zone, and is not conducive to the closure and filling of the structural surface, resulting in weak strength, abnormal fragmentation, and low density of the roadway surrounding rocks. At the same time, the direction of the roadway in this section of the roadway intersects with the maximum principal stress at a large angle. The high stress concentration of top slab caused by excavation is significantly destructive to the surrounding rocks. The roof and floor of the surrounding rocks experience deformation and fracture in a short period of time, which causes the two sides of the roadway to lose stability. Under the combined effects of unreasonable support strength and other factors, there are difficulties in stabilizing the roadway due to the creep of the surrounding rocks. The deformation lasts for nearly 3 months, and there is a large amount of cumulative deformation and damage.

4.2. Numerical Analysis of Roadway Instability. In order to analyze the influence of horizontal stress on the stability of surrounding rocks and provide a theoretical basis for the design of roadway support parameters, FLAC 3D simulation software is used to analyze the instability mechanism of surrounding rocks and the support and reinforcement scheme. In the 1621 (1) working face transportation roadway of Pansan Coal Mine, the row spacing between roof bolts is 750 mm × 800 mm, the row spacing between two anchor bolts is 800 mm × 800 mm. The bolt length is 2400 mm, and the anchorage length is about 1200 mm. The row spacing between roof anchor cables is 1500 mm × 800 mm. The size of the model is 50 m × 50 m × 100 m, and the roadway section is a straight wall rectangle, 3.50 m in width and 4 m in height. Schematic diagram of the model is shown in Figure 5.

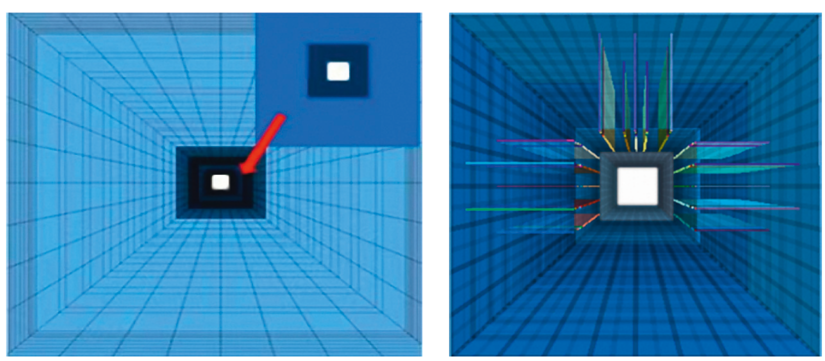
The ratio coefficient of the minimum horizontal principal stress σ_H is obviously larger than vertical stress σ_v. The coefficient of horizontal pressure σ_H/σ_v is 1.56–1.75. The ratio efficient K between the maximum horizontal principal stress σ_H and the minimum horizontal principal stress σ_h is 1.46–1.83. The surrounding rock simulation is calculated by the Mohr–Coulomb constitutive model, and the bolt is simulated by the cable element of the software. The elastic modulus of anchor bolt is 3.0×10^4 MPa. According to the buried depth model of the roadway, a vertical stress of 21.30 MPa is applied at the top, the maximum horizontal principal stress is 34.40 MPa, and the minimum horizontal principal stress is 19 MPa. The horizontal displacement is restricted, in addition to the minimum vertical displacement. The coal and rock mass parameters are shown in Table 1.

The surrounding rock stress was redistributed after the excavation of the roadway. As shown in Figure 6, the surrounding rocks of the roadway section are distributed with a certain thickness of the ring-shaped stress reduction zone. The principal stresses of the surrounding rocks are evenly distributed when the roadway is driven in the direction of the maximum horizontal principal stress and tended to be



(a) (b)

Figure 4: Distribution of lateral pressure coefficient with depth. (a) Distribution of lateral pressure coefficients in local mining areas in Shandong province. (b) Distribution of lateral pressure coefficients in local mining areas in Anhui province.



(a) (b)

Figure 5: Schematic diagram of the model. (a) Schematic diagram of the roadway section. (b) Schematic diagram of bolt support.

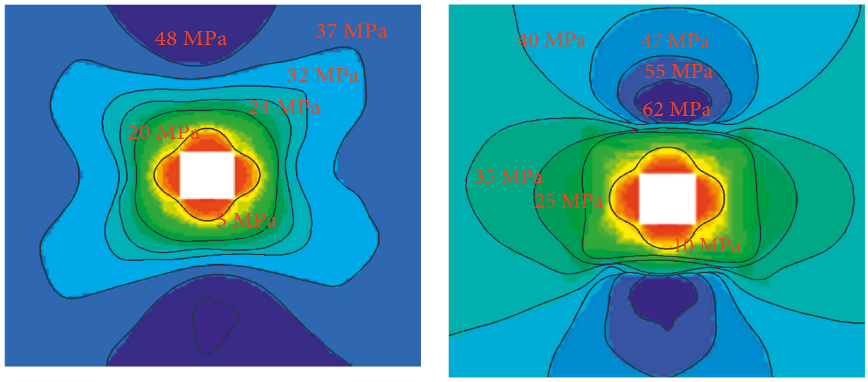
Table 1: Physico-mechanical parameters of the calculation model.

Lithology	Density (kg/m^3)	Tensile strength MPa	Bulk modulus, GPa	Shear modulus, GPa	Cohesion, MPa	Internal friction angle (°)
Rock formation	2.34	2.50	7.52	3.10	4.00	30
Coal seam	1.42	1.20	2.67	1.30	1.30	24

low. When the roadway is driven in the direction of the minimum horizontal principal stress, that is, when perpendicular to the maximum horizontal principal stress, concentrated area stress appeared on the roof and floor, and the area of increases stress expanded to the maximum range.

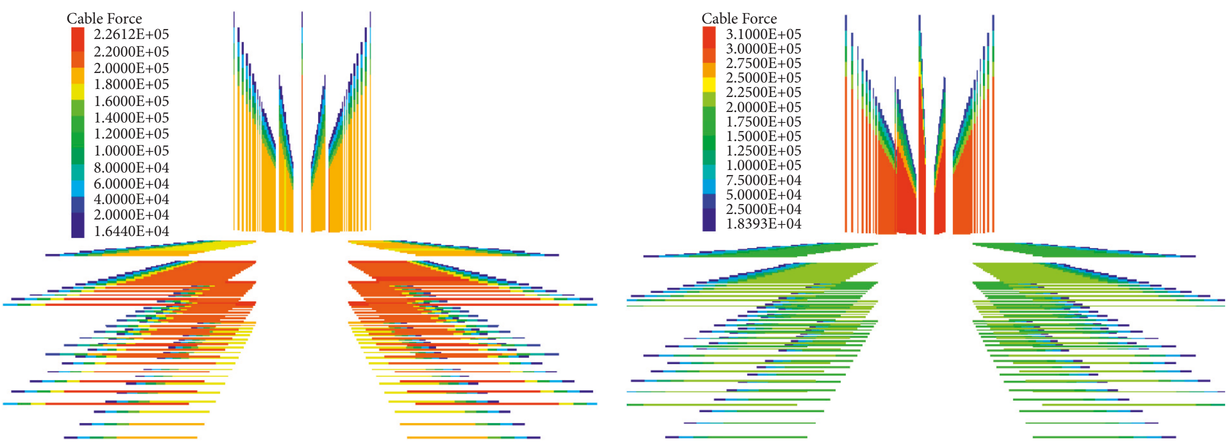
As shown in Figure 7, with the change of the direction of roadway excavation and the direction of maximum principal stress, the change of bolt support axial force also changes, which is consistent with the change trend of the surrounding rocks stress of the roadway.

Through the numerical simulation results and aforementioned analysis, a conclusion could be drawn that when the roadway was approaching parallel to the maximum horizontal principal stress, the overall condition of the roadway is better. In such circumstances, more attention should be paid to the deformation of the ledge on the roadway. When the direction of the roadway is close to the direction of the maximum horizontal principal stress, the roof and floor of the roadway are the focus of the support. In such circumstances, the key support areas need to increase



(a) (b)

Figure 6: Stress distribution of the surrounding rocks in the roadway. (a) Roadway parallel to the maximum horizontal principal stress. (b) Roadway perpendicular to the maximum horizontal principal stress.



(a) (b)

Figure 7: Bolt axial force distribution. (a) Roadway parallel to the maximum horizontal principal stress. (b) Roadway perpendicular to the maximum horizontal principal stress.

the strength of bolt support. Before the excavation of the roadway, the direction of the in situ stress distribution should be ascertained, and the roadway should be excavated as far as possible to avoid the vertical axis with the maximum horizontal principal stress. If there are difficulties in avoiding the vertical axis, a support plan should be designed according to the geological situation.

5. Conclusions

In the present study, the overall distribution characteristics of in situ stress in the Huanghuai mining area are analyzed, and the stress of the surrounding rocks of the roadway when the deep soft rocks roadway and the maximum horizontal principal stress are in an unfavorable direction and the force law of bolts is investigated. The main conclusions are as follows:

(1) The in situ stress fields in Anhui and Shandong mining areas are found to be mainly of the $\sigma_H > \sigma_v > \sigma_h$ type. The vertical stress in the mining areas of Anhui and Shandong provinces kept increasing with the increasing depth, and the vertical stress of the mining area is generally equal to the weight of the overlying rocks mass. There is a certain horizontal stress in the shallow part of the mining area, and the horizontal stress gradually increases with the development of the deep part. The horizontal stress is smaller than the vertical stress, and the horizontal stress dispersion is more significant.

(2) The mining areas of Anhui and Shandong provinces are dominated by horizontal stress. The lateral pressure coefficient of the Anhui mining area varied within 1.20–2.10, and the lateral pressure coefficient of the Shandong mining area varied within 0.90–2.70. The value of the lateral pressure coefficient varied in shallow areas. As the depth continued to increase, the lateral pressure coefficient gradually converged and tended to a fixed value.

(3) When the roadway is driven along the maximum horizontal principal stress, the stress of the

surrounding rocks of the roadway are distributed around the section, there is no stress concentration in the roadway, and the overall force of the anchor cable is even. When the roadway is driven in the vertical direction of the maximum horizontal principal stress, the maximum horizontal principal stress transferred to the top and bottom plates, the range of high stress areas on the top and bottom plates is significantly increased, and the degree of stress concentration is significantly increased. The force of the top anchor cable also significantly increased.

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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