HONGJUN GUO
MING JI
HAIZHU LI
KUN ZHANG
HUIQIN WANG
and
AOXIANG LIANG

Research and application on support technology of coal seam roadway with high stress

Based on the measured in-situ stress, the stress, displacement and plastic zone distribution in surrounding rock of the eastern 2# ventilation roadway of a mine in Shanxi are analyzed by using the generalized plane strain model, Mohr-Coulomb strength criterion and $FLAC^{3D}$ software. And it is considered that the stress concentration of surrounding rock is significantly affected by the circumferential stress in the range of 0~3m and the radius of plastic zone is 5m. Both of them have strong uniformity in distribution and it is approximately located in the direction of 135°-315°, showing the asymmetric characteristics. Combining with the influence characteristics of in-situ stress on the coal seam roadway, an asymmetric support scheme for roadway section is proposed. The practice shows that the support is effective, which provides theoretical guidance for the design and optimization of support parameters of roadway with similar engineering conditions.

Keywords: *In-situ stress; coal seam roadway; stress of surrounding rock; displacement of surrounding rock; asymmetric plastic zone; support design.*

1. Introduction

With the gradual reduction or exhaustion of coal resources, a change of China's coal mining pattern from the east to the west, from the shallow to the deep is taking place. Meanwhile, the environment of in-situ stress is becoming more complex, the mining conditions are being becoming increasingly harsh [1]. The in-situ stress is the main factor affecting the stability of surrounding rock of roadway. The increase of mining depth must lead to the change of stress field, which threatens the stability of surrounding rock of roadway and disturbs the safe and efficient production of mine.

The combined method of theoretical analysis and numerical simulation are used, the distribution of stress and plastic zone in surrounding rock of roadway are analyzed, and then the stability of surrounding rock of roadway with different layouts are comprehensively evaluated by Zhu Zhijie [2]; the asymmetric deformation mechanism of deep roadway is discussed by Meng Long [3]. Li Haijiang [4] made theoretical analysis and physical simulation are combined to study the characteristics and mechanism in deformation and failure of surrounding rock of the circular and rectangular roadways under high in-situ stress. By means of a comprehensive method of in-situ monitoring, the true triaxial geomechanical model test, theoretical analysis and numerical simulation, the forming mechanism and anchorage characteristic on the zonal failure of surrounding rock of deep roadway under high geostress are entirely researched by Chen Xuguang[5].

Through establishing a model of generalized plane-strain model, a formula of the relationship between the in-situ stress and the stability of surrounding rock of roadway are deducted by Liu Haiquan [6], the effect of the horizontal and vertical angle between the larger horizontal stress and the roadway axes on the stress and displacement in surrounding rock of roadway are analyzed. SMP (spatially mobilized plane) criterion is used, the influence of original rock stress on the stress of plastic zone is explored by Ye Jinsheng [7], and the expressions between the stress of plastic zone, and the support force and the original rock stress are obtained. The surrounding rock of roadway is divided into plastic residual zone, plastic softening zone and elastic zone by Jing Laiwang et al. [8]. On the basis of the Mohr-Coulomb strength criterion, considering the properties of dilatancy and softening, the analytic expressions of the stress and radius of plastic zone are calculated. In addition, a case is analyzed to study the effect of original rock stress on the stress, strain and softening modulus of plastic zone. According to the deformation spatio temporal effect of tunnel during construction, the theoretical solution on the deformation of surrounding rock of tunnel with high geo-stress is derived by Liao Xiong[9]. The research, which was developed from the geological conditions of surrounding rock, the deformation characteristics of soft rock and the effect construction, revealed the deformation mechanism, and the control measures are also proposed.

Messrs. Hongjun Guo, Ming Ji, Haizhu Li, Kun Zhang, Huiqin Wang and Aoxiang Liang, Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China; School of Mines; China University of Mining & Technology, Xuzhou, 221116, China. Corresponding author: e-mail: jiming@cumt.edu.cn

Through the united method of laboratory tests, in-situ stress measurement and numerical simulation, the deformation damage mechanism of roadway and bolts-grouting reinforcement mechanism are studied systematically [10, 11], and Liu Qinglin [12] put forward roadway as a whole object to bolts-grouting reinforcement; Meng Qingbin [13] expounded a combination support system with the inter-grouting anchor as the leading actress; and Yang Ziquan [14] proposed the first support with bolt-cable-mesh-shotcreting support and the second support with long annular compressible closed support along with backwall grouting combined support technology.

The FLAC 3D software is applied for the study on the weakening laws and discontinuous distribution of plastic zone of surrounding rock of roadway under high in-situ stress, and the effect of side pressure coefficients on the stress and displacement of surrounding rock by Zhu Yongjian [15]. And besides, a surrounding rock control technology is put forward for high strength, high stiffness and a wide range. Based on the stress field, the mechanism for effects of high crustal stress, high-level permeable pressure, and high temperature gradient on the stability of deep roadways are concluded by Liu Quansheng [16]. A dynamic design method of bolt support for coal seam roadway, which includes the steps of geostress test, geo-mechanics evaluation, initial design, in-situ measurement, information feedback and design revision are put forward by Yang Zhenmao et al. [17].

In view of the coal seam roadway under high stress conditions, this paper further discusses the stability of surrounding rock of roadway and the corresponding support measures.

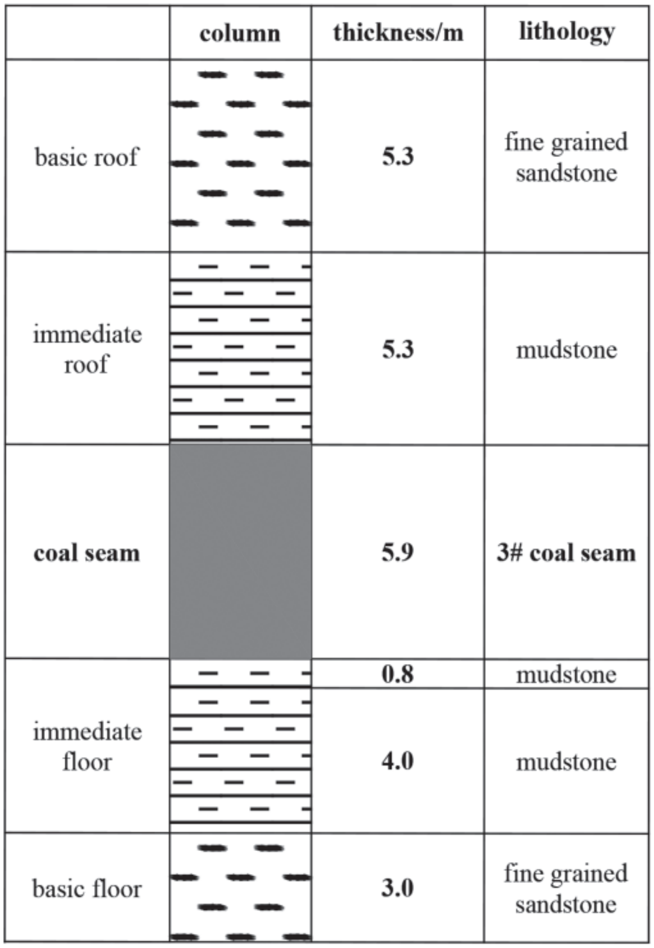

Fig.2 Roof and floor rock characters of 3# coal seam

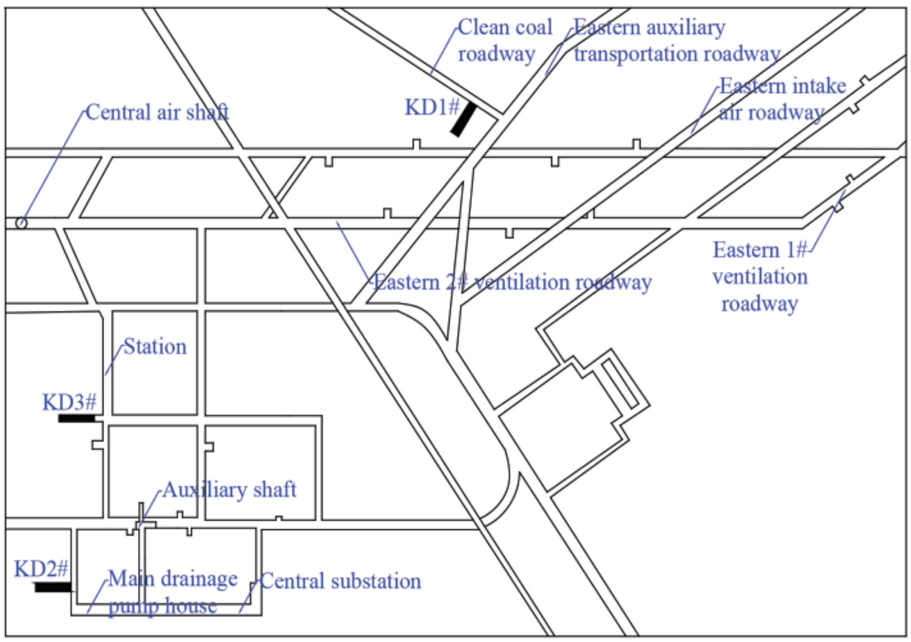

Fig.1 Layout of auxiliary shaft station

2. Engineering situation

The layout of the auxiliary shaft station in a coal mine in Shanxi is shown in Fig.1. The main roadways is basically designed along the 3# coal seam. The buried depth of coal seam is 551m. Its thickness changes greatly to 3.35-10.25m (average 5.9m). The coal seam with a dip angle of 4°-6° is incline to the west. The lithology distribution of roof and floor are shown in Fig.2.

The mechanical parameters of coal and its roof and floor, such as compressive strength, tensile strength, elastic modulus and poisson ratio, are obtained by field sampling, specimen processing and test (Fig.3). The specifics are shown in Table 1.

The stress relief method of hollow inclusion is used to measure in in-situ stress in +420m level of coal mine

Table 1 The parameters of surrounding rock in east 2# roadway for returning air

Coal and rock	Compressive strength/MPa	Tensile strength /MPa	Elastic modulus /GPa	Poisson ratio	Cohesion /MPa	Internal friction angle /°
Sandstone	19.65	2.86	4.8	0.25	3.48	32.94
3# coal seam	5.33	0.47	2.19	0.33	2.54	30.59
Mudstone	11.32	1.86	2.8	0.28	3.17	31.20

Table 2 The value and direction of In-Situ stress

Number	Stress	Value/MPa	Direction angle/°	Dip angle/°
KD1#	σ1	13.5	N190.60°E	69.87
	σ2	10.4	N10.94°E	20.13
	σ3	4.5	N100.90°E	–0.11
KD2#	σ1	14.2	N208.5°E	79.93
	σ2	12.3	N17.75°E	9.9
	σ3	6.1	N108.07°E	1.84
KD3#	σ1	13.8	N202.35°E	84.57
	σ2	11.6	N14.45°E	5.38
	σ3	6.7	N104.52°E	0.74

(Fig.1). The value and direction are given in Table 2. The vertical principal stress is dominant in the stress field. The average side pressure coefficient is 0.83, and the average ratio of horizontal principal stress is 0.5, which indicates that the horizontal stress is large and obviously directional. And the larger horizontal stress is mainly distributed in the range of N10°E-N20°E.

3.Theoretical analysis on the stability of surrounding rock of roadway without support based on in-situ stress

3.1 Distribution laws of stress and displacement in surrounding rock of roadway

This paper takes the Eastern 2# ventilation roadway near KD1# measuring point as an example. The roadway with rectangular section, width×height = 5.5×4.5m is excavated along the roof of coal seam, and its axial azimuth angle is N10°E. According to the generalized plane strain model, the formula of stress and displacement in surrounding rock of circular roadway is [6]

$$
\left.\begin{aligned}
\sigma_r &= \frac{\sigma_x+\sigma_z}{2}(1-\frac{a^2}{r^2})+\frac{\sigma_x-\sigma_z}{2}(1+\frac{3a^4}{r^4}-\frac{4a^2}{r^2})\cos 2\theta+\tau_{xz}(1+\frac{3a^4}{r^4}-\frac{4a^2}{r^2})\sin 2\theta \\
\sigma_\theta &= \frac{\sigma_x+\sigma_z}{2}(1+\frac{a^2}{r^2})-\frac{\sigma_x-\sigma_z}{2}(1+\frac{3a^4}{r^4})\cos 2\theta-\tau_{xz}(1+\frac{3a^4}{r^4})\sin 2\theta \\
\sigma_{y'} &= \sigma_y-\mu\left[2(\sigma_x-\sigma_z)\cos 2\theta+4\tau_{xz}\sin 2\theta\right]\frac{a^2}{r^2} \\
\tau_{r\theta} &= -\frac{\sigma_x-\sigma_z}{2}(1-\frac{3a^4}{r^4}+\frac{2a^2}{r^2})\sin 2\theta+\tau_{xz}(1-\frac{3a^4}{r^4}+\frac{2a^2}{r^2})\cos 2\theta \\
\tau_{ry} &= (\tau_{xy}\cos\theta+\tau_{yz}\sin\theta)(1-\frac{a^2}{r^2}) \\
\tau_{\theta y} &= (-\tau_{xy}\sin\theta+\tau_{yz}\cos\theta)(1+\frac{a^2}{r^2})
\end{aligned}\right\} \quad \ldots 1
$$

where, $\sigma_r(\sigma_\theta,\sigma_{y'})$ is the radial (circumferential and axial) stress in surrounding rock of circular roadway, $\tau_{r\theta}(\tau_{ry},\tau_{\theta y})$ the shear stress in surrounding rock of roadway in cylindrical coordinate system, θ the angle between the radial direction of the plane of xoy and the axis of ox, a the radius of circular roadway, 3.55m, r the distance between radial arbitrary point of circular roadway and the base point of O, $\sigma_x(\sigma_y,\sigma_z,\tau_{xz},\tau_{xy},\tau_{yz})$ the stress components in the space rectangular coordinate system.

$$
\left.\begin{aligned}
u &= \frac{1+\mu}{E}\frac{a^2}{2r}\left\{(\sigma_x+\sigma_z)+(\sigma_x-\sigma_z)\left[-\frac{a^2}{r^2}+4(1-\mu)\right]\cos 2\theta \right. \\
&\quad \left. +\frac{\tau_{xz}a^2}{r^2}\left[-\frac{a^2}{r^2}+4(1-\mu)\right]\sin 2\theta\right\} \\
v &= -\frac{1+\mu}{E}\frac{a^2}{2r}\left[(\sigma_x-\sigma_z)\sin 2\theta-2\tau_{xz}\cos 2\theta\right]\left[\frac{a^2}{r^2}+2(1-2\mu)\right] \\
w &= \frac{2(1+\mu)}{E}\frac{a^2}{r^2}(\tau_{yz}\sin\theta+\tau_{xy}\cos\theta)
\end{aligned}\right\}
$$

where, $u(v,\ w)$ is the radial (circumferential and axial) displacement in surrounding rock of roadway, μ the poisson ratio, E the modulus of elasticity.

The measured stress of KD1# measuring point is transformed into the space rectangular coordinate system. Suppose θ be 0°, 39°, 90°, 141°, 180°, 219°, 270° and 321° respectively (i.e. roof, floor, two sides and four sharp corners of roadway). The stress and displacement in surrounding rock of roadway without support with the radial distance (15m away from the roadway surface) are obtained by formulas (1) and (2), as shown in Fig.5 and Fig.6.

As shown in Fig.3, when the distance from the roadway surface along the radial direction increases, the stress in surrounding rock varies from at different positions of roadway. On the whole, the stress in surrounding rock of roadway varies sharply in the range of 0-3m, changes gently in the range

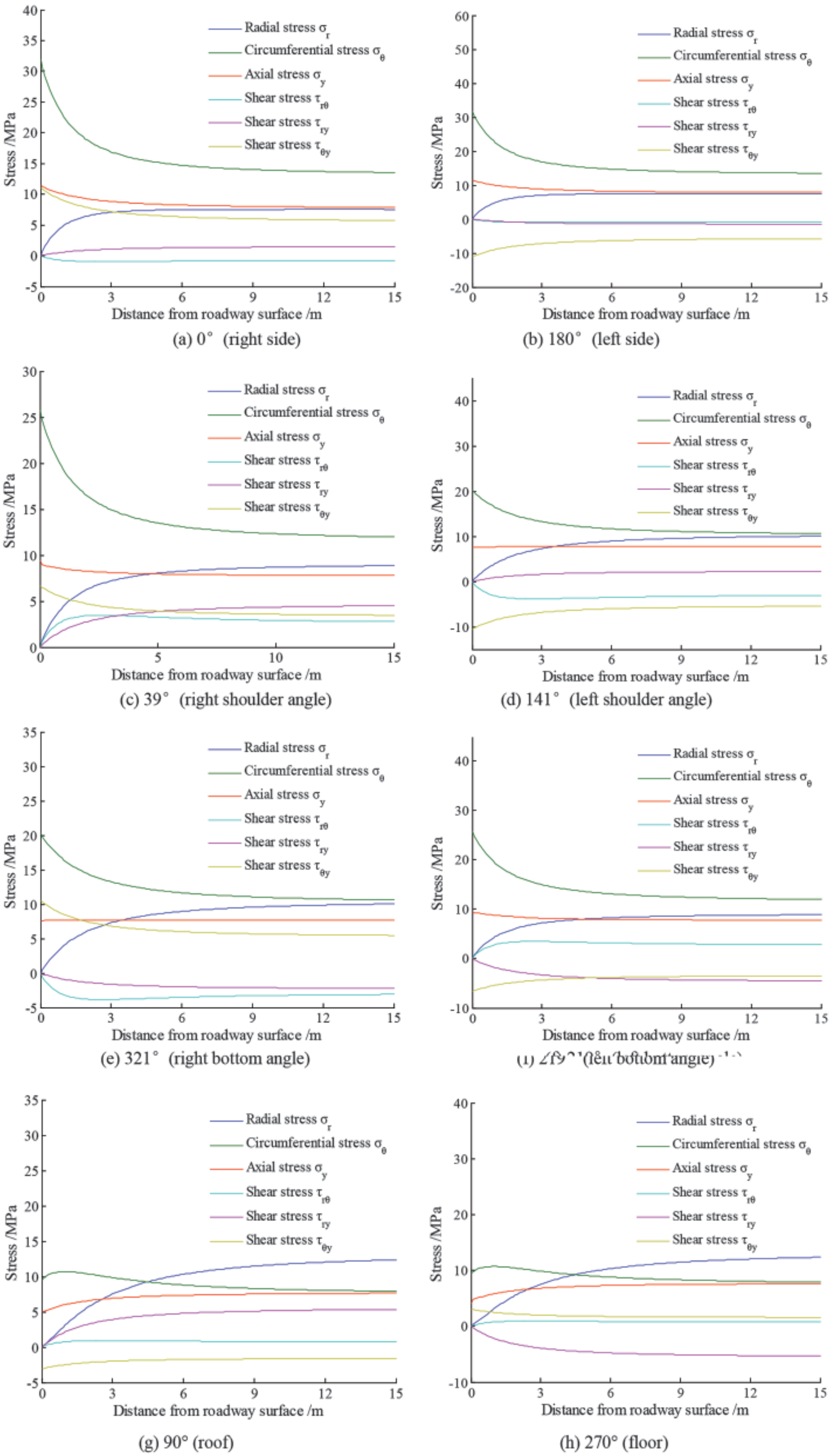

Fig.3 Stress distribution in surrounding rock of roadway without support

of 3-8m, and tends to be stable beyond 8m. The circumferential stress dominates in surrounding rock of two sides and is more than 30MPa in the surface or shallow of roadway. The radial stress and axial stress changes little, and stabilizes around 10MPa. In addition, the shear stress is not significant. The stress distribution in surrounding rock of roadway corner is similar to that of two sides, and the circumferential stress in the shallow of roadway is 20-25MPa. The stress in surrounding rock of roof and floor is relatively small, and the circumferential stress come into prominence in the shallow (0-4.5m), the radial stress in the deep part (4.5~15m).Therefore, the control and maintenance for the surrounding rock of two sides are more important in the excavation and support process of eastern 2# ventilation roadway [18].

From Fig.4, it can be seen that the displacement distribution in surrounding rock of roadway is similar to the stress distribution with the radial distance changing. Within the range of 0-3m, the displacement changes are dramatic, and the changes in 3~8m range slow down and tend to be stable. With the increase of radial distance, the displacement in surrounding rock gradually decreases to zero. The radial displacement is obviously greater than the circumferential displacement and axial displacement, and the direction of radial displacement is the same, but the direction of the latter two is not entirely identical. The maximum displacement of two sides is about 25mm, the maximum displacement of roof and floor about 45mm. Because the roadway is excavated along the roof, there is 1.4-meter coal

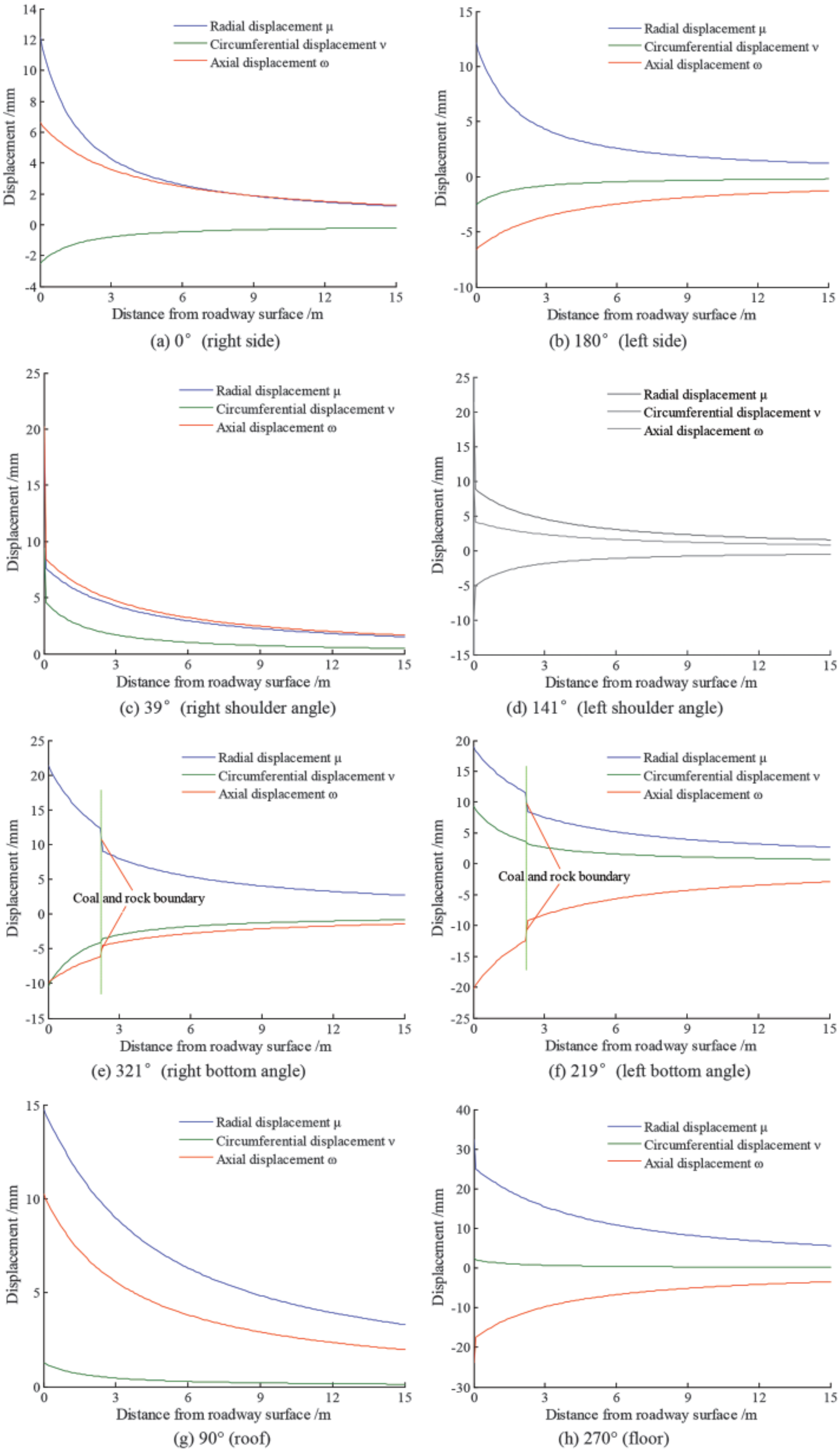

Fig.4 Displacement distribution in surrounding rock of roadway without support

seam left below the floor of roadway, resulting in the displacement discontinuity in the boundary between coal and rock in surrounding rock at two roadway corners.

3.2 Distribution laws of plastic zone in surrounding rock of roadway

According to Mohr-Coulomb strength criterion, the plastic zone distribution in surrounding rock of roadway without support is calculated by combining in-situ stress with the mechanical parameters of surrounding rock, as shown in Fig.5.

As can be told from Fig.5, the plastic zone is asymmetrically distributed, mainly in the direction of 135° (left shoulder corner)-315° (right bottom corner), which is consistent with the stress distribution law. That is, it is the key factor for the design of support parameters. The plastic zones of two sides are close to 5m, and that of roof and floor are relatively small, 1.6m and 1.8m respectively.

4. Numerical simulation analysis on the stability of surrounding rock of roadway without support based on in-situ stress

In combination with the actual engineering conditions, the distribution of stress, displacement and plastic zone in surrounding rock of eastern 2# ventilation roadway are calculated by using FLAC^{3D} simulation software, as shown in Figs.6 to 8.

From Fig.6 to 8, it can be known that the stress distribution in surrounding rock is asymmetrical, and the stress concentration coincides with M-C distribution of plastic zone. The maximum stress is 22.63MPa, which is 1.6-2.0m

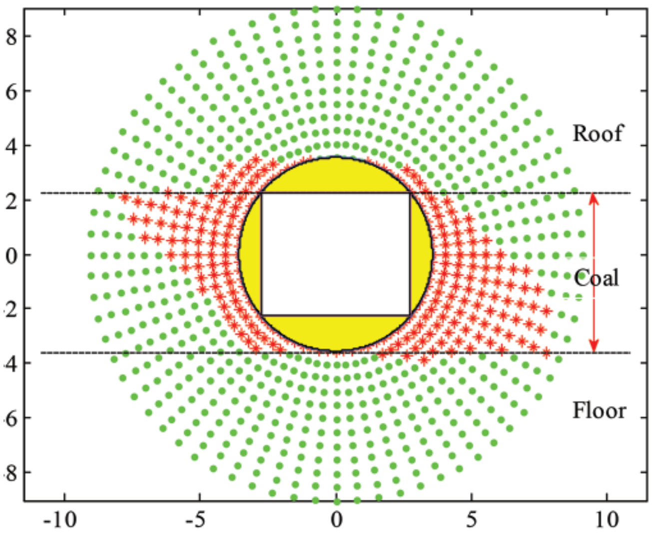

Fig.5 M-C distribution of plastic zone in surrounding rock of roadway without support

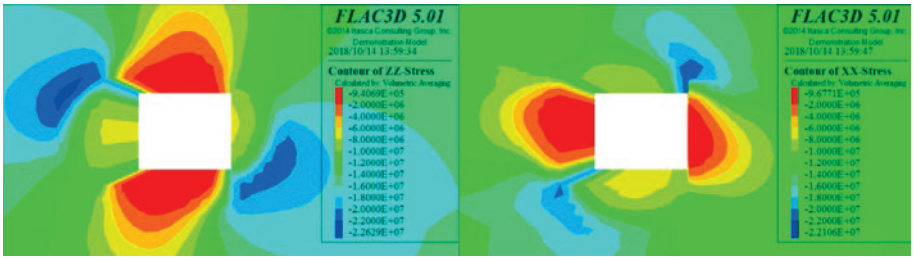

Fig.6 Stress distribution in surrounding rock of roadway without support

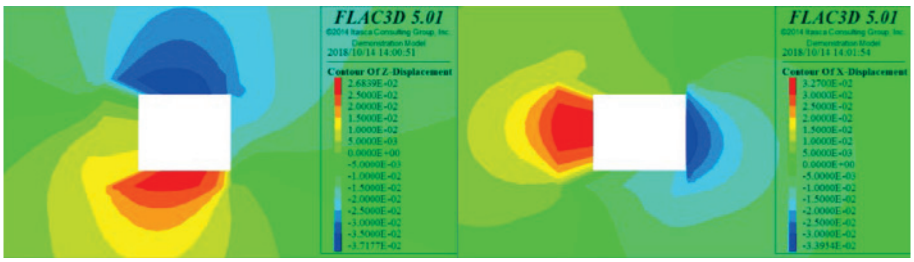

Fig.7 Displacement distribution in surrounding rock of roadway without support

away from the roadway surface. The convergence of two sides is about 67mm, the convergence between roof and floor 64mm. Moreover, the roof subsidence is slightly greater than the floor heave.The distribution of plastic zone is also asymmetrical. The plastic zone of two sides and floor is larger, about 2.0-2.5m, and the radius of plastic zone of roof is smaller, about 1.5m, which is related to excavation along the roof.

In summary, under the action of actual in-situ stress, the stress concentration and plastic zone in surrounding rock of eastern 2# ventilation roadway are identical, and the section is asymmetric. Therefore, the requirements for the design of roadway support parameters are put forward, and the theoretical basis is also provided.

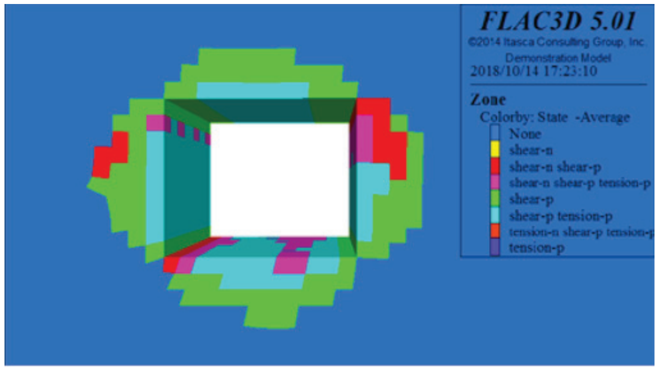

Fig.8 Plastic zone distribution in surrounding rock of roadway without support

5. Support design and industrial test

Based on the theoretical calculation of bolt-cable parameters and the distribution laws of stress, displacement and plastic zone in surrounding rock of roadway without support under high in-situ stress, the unsymmetrical support scheme of eastern 2# ventilation roadway is proposed [12]. Namely, the column spacing of bolt is reduced in the area of left shoulder corner and right bottom corner of roadway, and the support section is shown in Fig.9.

According to the actual situation of roadway, without affecting the progress of construction, the full length anchorage of cement slurry with low pressure is selectively carried out at a certain distance (about 20m) behind the heading, so as to improve the shallow surrounding rock structure and strengthen the effect of bolt support [16]. Through the field observation, the section convergence is given in Fig.10.

It can be seen from Fig.10 that the accumulative convergence between roof and floor is near 310mm, the two sides' 130mm, and the section convergence is mainly caused by the movement of roof and floor. But no deformation has been observed when the stress environment rebalanced again. It indicates that the support parameters are reasonable and the support is effective, ensuring the stability of the surrounding rock of roadway and laying a foundation for the support of high stress coal seam roadway.

6. Conclusions

Through the research on the stability of surrounding rock and support technology of high stress coal seam roadway, the following conclusions are drawn:

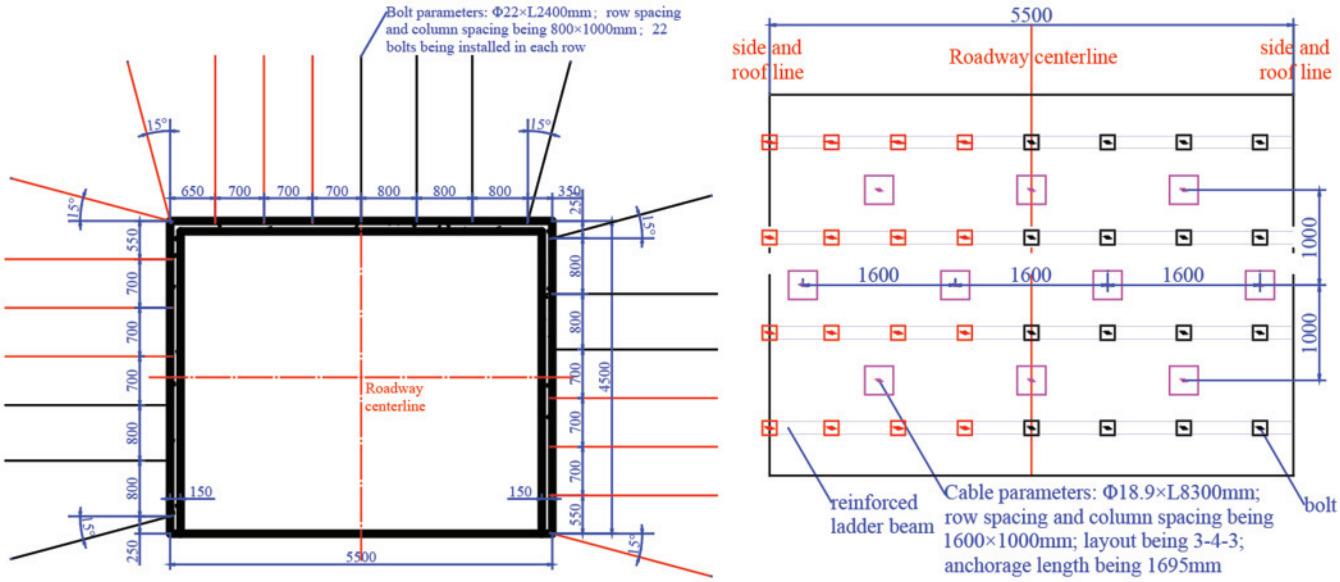

Fig.9 Support section of roadway

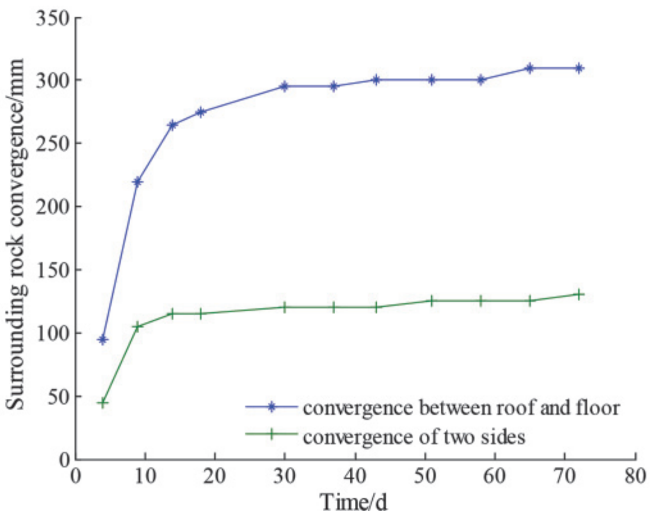

Fig.10 Convergence statistics of roadway section

1. Combined with the measured in-situ stress, the distribution of stress and displacement in surrounding rock of roadway are analyzed by using the generalized plane strain model. The stress and displacement in surrounding rock of roadway vary sharply in the range of 0-3m, and change gently in the range of 3-8m, and tend to be stable 8m away. The stress is mainly circumferential stress and the two sides are significantly affected by it. Also, the displacement is mainly radial displacement.
2. Based on Mohr-Coulomb strength criterion, the radius of plastic zone in surrounding rock is obtained and 5m, which is concentrated in the direction of 135°-315°. It is consistent with the stress distribution law in surrounding rock of roadway, which is the key factor for the design of roadway support.
3. By simulating the distribution of stress, displacement and plastic zone in surrounding rock of roadway without support in high stress coal seam, the characteristics of stress concentration and the asymmetric distribution of plastic zone in surrounding rock are further explained.
4. Considering the influence of the actual stress on the coal seam roadway and the key control of the fragile area of surrounding rock, the asymmetric support scheme of roadway section is put forward.Through the field observation, the accumulative displacement between roof and floor is nearly 310mm, the two sides' 130 mm. And there is no displacement observed after the surrounding rock of roadway is stable again, which proves that the support is effective.

Data availability

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

Conflicts of interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

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