ZHANG KUN
JI MING
GUO HONGJUN
and
HE WENRUI

Study on reasonable width of coal pillar in thick coal seam section

The key to the selection of coal pillar width lies in the stability of the roadway space and the stability of the coal pillar itself. Based on the theory of coal pillar stress distribution, the reasonable retention width of the coal pillar in the deep buried thick coal seam is discussed. Reasonable coal pillar width and scientific roadway support parameters can maximize the bearing capacity of the surrounding rock, improve the stability of the roadway and reduce the coal mining loss. Reducing the size of existing large coal pillars in a stable stress interval is of great significance for coal mines to increase production and green mining. Through theoretical analysis, numerical simulation and on-site measurement, the stress, strain and displacement of the coal pillar are analyzed, and the width of the section coal pillar is reduced to a safe and scientific scope, supplemented by engineering verification.Therefore, it provides a reference for the narrow coal pillar mining in thick coal seam; learn from the meaning.

Keywords: *Thick coal seam; coal pillar width; coal pillar stress; reasonable width*

1. Introduction

For a long time, the maintenance of section the coal pillar in the reserved section is always the main way to isolate the goaf and maintain the roadway in the lower section of coal mine in China [1]. From the domestic and international research and development trends, there are mainly two ways to retain the section coal pillars. The first one is the wide coal pillar method, which arranges the roadway outside the pressure peak to reduce the damage to the roadway; the other one is narrow coal pillars or non-coal pillars, the coal pillar size is reduced and resource waste is reduced [2]. The research and development level of the two ways of protecting the lanes also have their own characteristics, and they are widely used under different conditions. China's central and western coal mines gradually began to enter the deep thick coal seam mining stage, but the actual production process of most existing coal mines has been plagued by the retention of coal pillar size, and more than 40m coal pillars are selected for retention. It is not only impossible to recover large coal pillars, but also to stay in the stress peak area, which is an important cause of major accidents [3]. Especially in the case of scientific and green mining, the requirements for the determination of the width of coal pillars are put forward.

Messrs. Zhang Kun, Ji Ming, Guo Hongjun and He Wenrui, Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China; School of Mines; China University of Mining & Technology, Xuzhou, 221116, China. e-mail: jiming@cumt.edu.cn

Now taking the 41 disk area of Wenjiapo mine in Binchang mining area as the engineering background, Wenjiapo mine is mainly mine No.4 coal seam with a depth of 650m. The thickness of coal seam is 0.8~14.61m, the average thickness is 4.8m. Wenjiapo adopts large mining, fully high mechanized coal mining method and fully mechanized top coal caving mining method. The width of the coal pillars in the face is 44.5m, which is shown in Fig.1. The coal pillars are broken when mining, the stability of the surrounding rock of the roadway is poor, and the width of the coal pillars needs to be improved.

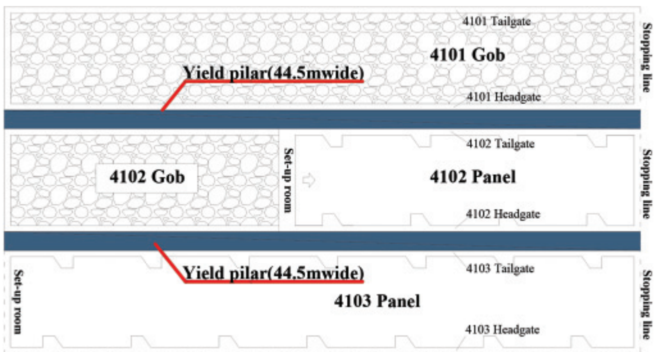


Fig. Schematic diagram of the project

2. Theoretical analysis of stress distribution of coal pillar

After mining on the side of a section of coal pillar, the overburden pressure is redistributed, and a certain range of supporting stress bands are formed inside the coal pillar. Because of the effect of supporting force, it is considered that the coal and rock mass have been destroyed in a certain depth of coal pillar. It is generally believed that the supporting stress at the edge position of the section coal pillar is zero. With the increase of the depth, the supporting stress is gradually increased until the peak of the supporting stress of the section coal pillar is reached [4]. A specific region from the coal pillar boundary to the peak of the supporting stress is called the section coal pillar yield zone, also called the plastic zone width inside the section coal pillar.

In this section, the section coal pillar is divided into the inner plastic zone and the elastic zone. According to the quadratic curve, the theory calculates the coal body stress in the plastic zone through the limit equilibrium, and then the internal stress of coal pillar is obtained by substituting relevant parameters, and the reasonable width of coal pillar is determined finally. The relevant parameters obtain the internal stress of the coal pillar, and finally determine the reasonable coal pillar width. In the theoretical calculations, some necessary assumptions must be made to make the solution of the questions simple. The basic assumptions are as follows:

1. Coal pillars are regarded as ideal elastic bodies, which conforms to the reasonable assumptions of continuity, complete elasticity, uniformity and isotropy in elasticity;
2. Internal shear force damage of coal pillars meets the Mohr Coulomb criterion;
3. The stress limit equilibrium zone is at the elastoplastic boundary;
4. The influence of working face mining on the internal stress of adjacent coal pillars is: the stress limit equilibrium in the plastic zone of the roadway surrounding rock, and the internal stress in the post-peak region satisfies the Weber distribution;
5. The displacement and deformation inside the section pillar are small before yielding.

2.1 Stress distribution in coal pillar after mining face mining

When the recovery of the working face on one side of the mining roadway is completed, the stress distribution in the coal body is shown in Fig.2.

As the Fig.2 shows, $F(\varepsilon)$F shows the influence of working face mining on the internal stress of the solid coal in the right side. $f_1(\varepsilon)$ is the influence on the stress of the coal body in the plastic zone, and the vertical stress of coal pillar within plastic zone (within the peak value of lateral abutment pressure) is in the limit equilibrium state. $f_2(\varepsilon)$ is the influence on the stress of the coal body in the elastic zone [5].

It can be calculated by equation (1).

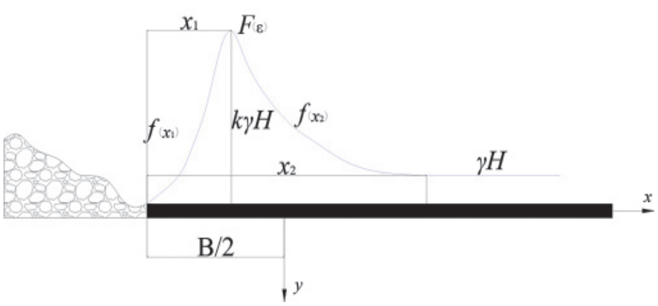


Fig.2 Stress distribution in the coal pillar after coal mining

$$f_1(\varepsilon)=\begin{cases}\left(\frac{C_0}{\tan\varphi}+\frac{p_i}{\lambda_1}\right)e^{\frac{2\tan\varphi}{m\lambda_1}\varepsilon+(B/2)}-\frac{C_0}{\tan\varphi}, & \varepsilon\in[-B/2,\ x_1-B/2) \\ (k_1-1)\lambda\, Hse^{1-s}+\gamma H, & \varepsilon\in[x_1-B/2,+\infty)\end{cases} \quad \text{... 1}$$

In the formula:

C_0 – cohesion at the coal seam interface, 6.62 MPa;

φ – The internal friction angle of the coal seam interface, 28.81°;

p_i – Bolt support strength, 0.2MPa;

λ_1 – Internal stress lateral pressure coefficient of coal pillar near working face, 1

m – roadway height, 3.8m;

B – the width of the coal pillar, 44.5m;

X_1 – Plastic zone range after mining face, m

The plastic zone range is calculated by equation (2).

$$x_1-\frac{m\lambda_1}{2\tan\varphi}\ln\left[\left(k_1\gamma H+\frac{C_0}{\tan\varphi}\right)\Big/\left(\frac{C_0}{\tan\varphi}+\frac{p_i}{\lambda_1}\right)\right] \quad \text{...2}$$

In the formula:

K_1 – the increase coefficient of the internal stress of the coal seam in the mining face.

The internal stress of the coal pillar outside the plastic zone satisfies the Weibull distribution, and the Weibull distribution function expression is:

$$w(x)=\mathrm{e}\frac{x}{x_w}e^{-\frac{x}{x_w}} \quad \text{... 3}$$

In the formula:

x_0 –random variable, that is, distance from the roadway wall

x – random variable, ie distance from the roadway wall

Xw – Parameters that regulate the degree of urgency of functions

According to the formula (2), combined with the distribution law of the internal stress of the coal pillar outside the plastic zone, the relevant parameters are substituted, among them, $f_2(\varepsilon)$ is:

$$f_2(\varepsilon)=(k_1-1)\,\gamma Hse^{1-s}+\gamma\mathrm{H},\ \varepsilon\in[x_1-B/2,+\infty) \quad \text{... 4}$$

In the formula:

$$s=\left(\varepsilon+x_f+B/2-x_1\right)\Big/x_{f0} \quad \text{... 5}$$

γ – Volume density, 2.5kN/m^3

H – the depth of the roadway, 650m;

X_f – the parameter that adjusts the urgency of the function.

In equation 4, $f_2(\varepsilon)$ is a unimodal function, when = x_1–

B/2, the peak value $f_2(\varepsilon)$ = k1γH. The stress peak increases as $k_1$increase, the stress peak can be adjusted by changing k_1 to reflect the influence of the mining face on the peak pressure of the coal pillar center. By increasing or decreasing X_ρ to adjust the slowness and urgency of during $f_2(\varepsilon)$ is declined. As it develops deep into the coal body, it gradually decreases to the original rock stress. According to the above analysis, the influence of the working face mining on the central stress of the coal pillar is

$$f_1(\varepsilon)=\begin{cases}\left(\dfrac{C_0}{\tan\varphi}+\dfrac{p_i}{\lambda_1}\right)e^{\frac{2\tan\varphi}{m\lambda_1}(\varepsilon+\mathrm{B}/2)}-\dfrac{C_0}{\tan\varphi},\varepsilon\in[-B/2,\ x_1-B/2) \\ (\mathrm{k}_1-1)\lambda\,\mathrm{Hse}^{1-s}+\gamma H,\varepsilon\in\left[x_1-B/2,+\infty\right)\end{cases} \quad ...6$$

2.2 Theoretical calculation of reasonable width of retained coal pillars

According to the geological conditions of the production of Wenjiapo mine and related test results, combined with the numerical simulation results, the calculation parameters are as follows: the average buried depth of the roadway is H = 650m, the density of the rock formation (ρ) is 2.5×103kg/m^3, the thickness of the coal seam (m) is 4.8m, the anchor supporting strength (pi) is 0.2 MPa, coal seam cohesion (C_0) is 6.62MPa, coal seam internal friction angle (φ) is 28.81°, solid coal support stress increase coefficient 1.5 after working face mining, plastic zone inner pressure coefficient is 1.0, coal after tunnel excavation. The body side support pressure increase factor of 1.3, and the plastic zone inner pressure coefficient is of 1.0.

The basic condition for maintaining the stability of the roadway is: after plastic deformation on both sides of the coal pillar, there is a certain width of elastic core in the center of the coal pillar, and the width of the elastic core is not less than twice the height of the coal pillar [5]. Therefore, the reasonable width of the coal pillar in the side section of the return airway of the 4102 working face is:

$$B > x_0 + 2m + x_1 \quad ...\ 7$$

$$x_0=\frac{m\lambda_1}{2\tan\varphi}\ln\left[\left(k_1\gamma H+\frac{C_0}{\tan\varphi}\right)\Big/\left(\frac{C_0}{\tan\varphi}+\frac{P_i}{\lambda_1}\right)\right] \quad ...\ 8$$

In the formula:

x_0 – the width of the plastic zone on the left side of the coal pillar

x_1 – the width of the plastic zone on the right side of the coal pillar

λ_1 – The solid coal support stress increase factor of 1.5 after mining

k_1 – the inner pressure coefficient of the plastic zone is 1.0

λ_2 – the increase coefficient of support pressure on the side of coal body is after excavation of roadway 1.3

k_1 – the inner pressure coefficient of the plastic zone is 1.0

Refer to Author ... (9)

Due to the different width of the coal pillars, the width of the corresponding coal column plastic zone is also different. Substituting the parameters to solve the equations 7, 8, 9, get 2m = 9.6, and obtain x_0= 11.2, x_1 = 8.9, then B>29.7.

3. Measurement of lateral stress in working face

The stress distribution in the coal pillars during the mining of the 4102 working face is measured by a borehole strain gauge to analyze the stress distribution of the coal pillar. Due to the large size of the coal pillars, the construction of horizontal small diameter deep holes is difficult, and the borehole cannot directly penetrate the 44.5 m coal pillar. Therefore, the two lanes are arranged in equal order, and the stations are arranged in front of the working face, that is, 4102 headgate and 4103 tailgate. The drilling depths are 3m, 6m, 9m, 12m, 15m, 18m and 21m, and the hole spacing is 1m, as shown in Fig.3(a).

The measured data is collected and incrementally processed and the curve is drawn to obtain the pressure distribution of the inner support pressure of the coal pillar, as shown in Fig.3(b).

It can be seen from Fig.3(a): as the working face is advanced, the inner bearing pressure of the coal pillar increases continuously under the influence of mining. The stress distribution in the coal pillar presents the form of “two

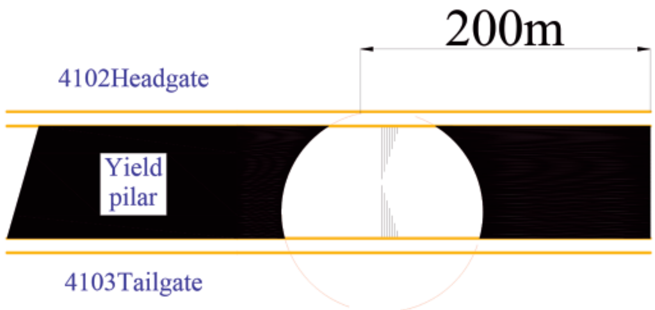


Fig.3(a) Drilling stress meter monitoring station

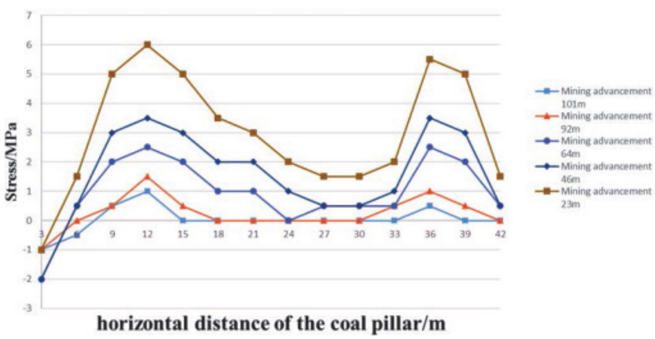
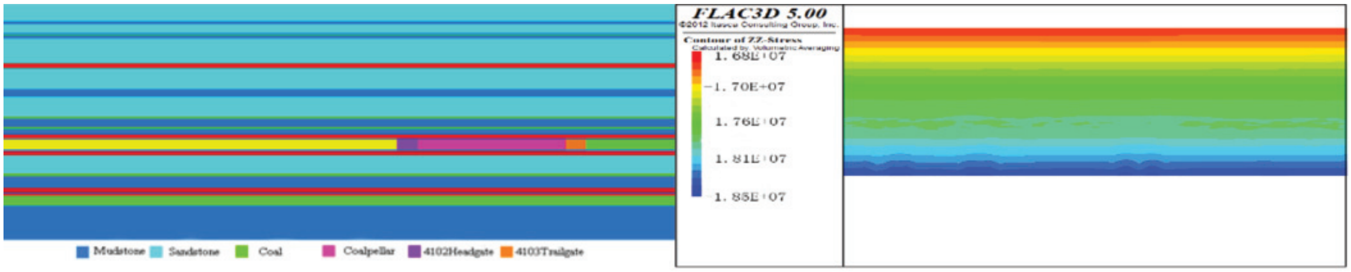


Fig.3(b) Incremental distribution of lateral support pressure of coal pillars



(a) Numerical model (b) Initial balance

Fig.4 Establishment of the FLAC3D numerical model

peaks and one valley". The positions of the two peaks are about 12m and 36m in the coal pillar, and the width is 24m. The peak increments are 7MPa and 6.5MPa, respectively. The "valley" of the stress curve is about 17m~34m. In the range of 17m width, the support pressure of the coal pillar is at a gentle and low level, and the stress value does not change much. It can be regarded as an elastic zone with a certain width in the coal pillar and has a strong bearing capacity. The analysis can be obtained: the width of the coal pillar can be appropriately reduced, and the "double peak" of the stress distribution of the coal pillar can be moved closer to the "valley" to reduce the width of the "valley", but still have enough elastic zone to play the bearing role [6]

Through the actual measurement, we can conclude:

It is recommended that the optimization of the coal pillar can reduce the width of the "valley", and its width can be reduced from 44.5m to 10m~18m, which is reduced to 26~35m.

4. Numerical simulation analysis of stress distribution of coal pillar

Using FLAC 3D software, under the condition that the 4102 working face side mining and 4103 roadway have been formed and affected by the mining of 4102 mined-out area, the stress distribution state in the width direction of the coal pillar and the deformation and destruction process of the two-section mining roadway are carried out. Simulation analysis, which provides guidance for the rational determination of coal pillar width.

4.1 Model establishment and parameter selection

According to the geological conditions of Wenjiapo mine, a numerical calculation model of FLAC 3D is established. The model consists of No.4 coal and its upper and lower rock layers totaling 28 layers. The total thickness of the model is 91m and the width is 206m. The axial direction of the roadway is 150m, that is, the model size is 206×150×91m. The horizontal displacement constraint is applied to both the boundary and the front and rear boundaries, the vertical displacement constraint is applied to the bottom boundary, and the uniform load is applied to the upper boundary. The uniform load is calculated according to the self-weight of the overburden. The density of the overlying strata is 2500kg/m^3, and the buried depth of No.4 coal seam is determined to be 650m. The uniform load of 16.95MPa is applied to the upper part of the model, and the self-weight of the overlying strata is simulated. The lateral pressure coefficient is taken as 1.

Table 1 Model coal rock parameter table

Lithology	Tensile strength/ MPa	Cohesion/ MPa	friction/°	Bulk modulus /K	Shear modulus /G
Mudstone	1.25	1.70	26.44	0.82	0.49
Sandstone	1.51	1.47	23.16	0.70	0.46
Siltstone	1.43	3.14	35.85	1.07	0.77
Coal	0.72	1.99	26.81	0.35	0.14

According to the measured results of the mechanical parameters of the rock mass of Wenjiapo mine, the mechanical parameters of the rock mass of the model are determined, as shown in Table 1.

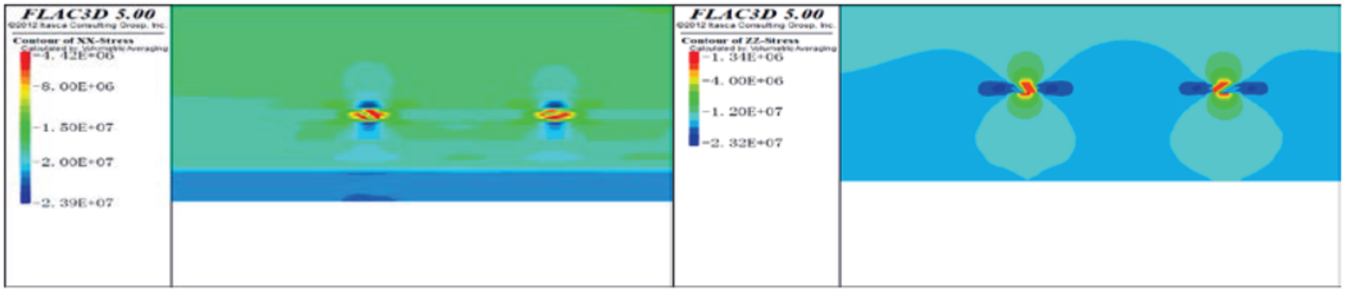
The numerical calculation model and the initial stress balance are shown in Fig.4.

4.2 Model solving

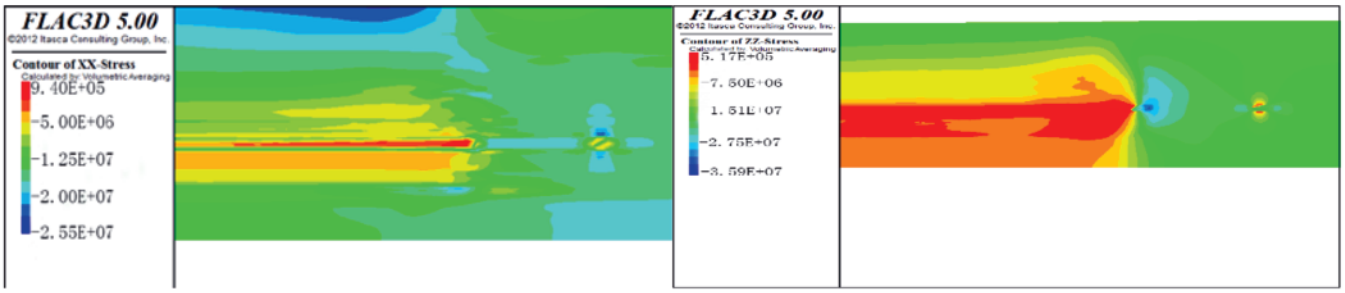
Simulate the calculation of the stress distribution in the coal pillars at 0m (4102 back and 4103 backtracking end), 40m, 80m, 120m, respectively, and the stress distribution in the coal pillar obtained is shown in Fig.5.

The stress distribution data obtained by numerical simulation is plotted as a curve, as shown in Fig.6.

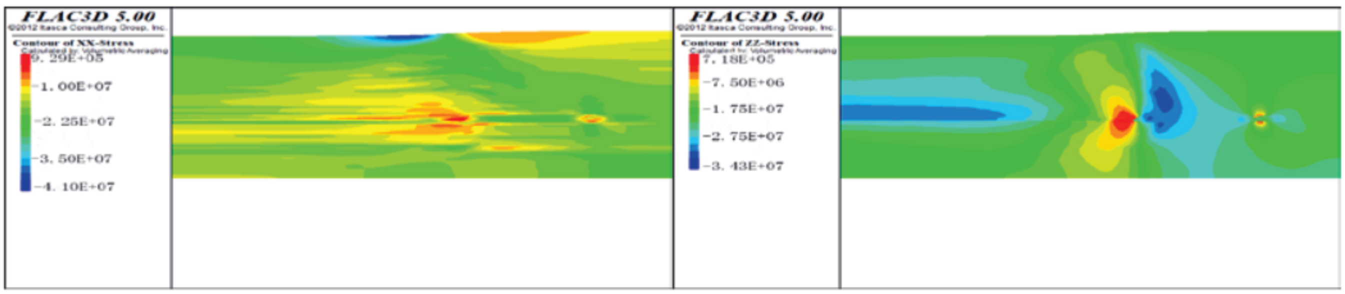
It can be seen from Fig.6 that with the advancement of the working face, the bearing pressure in the coal pillar increases continuously under the influence of mining.The stress distribution curve of the coal pillar in the face shows the form of "double peak and one valley", and the double peak of each curve. The positions are approximately 11m and 37m respectively in the coal pillars between the faces, and the range of the valley; "valley" is approximately in the range of 17m to 36m. In the range of 19m width of "valley", the support pressure of the section coal pillar between the working faces is at a gentle and low level, and the change of the stress peak is small, which can be regarded as a certain width of the elastic zone in the coal pillar. Strong bearing capacity [7]; the other range of coal in the pillar has yielded plastically and only has a certain bearing capacity, which can reduce the width of the "valley" in Fig.6.



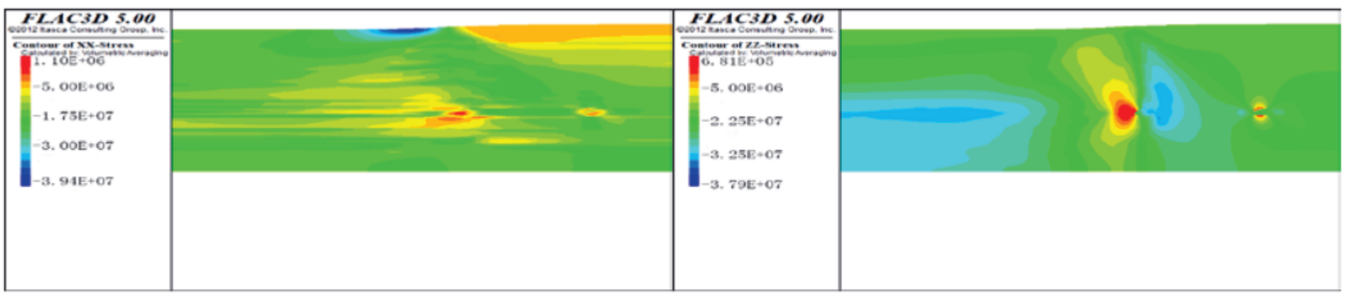
(a1) horizontal stress (advances 0m) (a2) vertiacl stress (advances 0m)



(b1) horizontal stress (advances 40m) (b2) vertiacl stress (advances 40m)



(c1) horizontal stress (advances 80m) (c2) vertiacl stress (advance 80m)



(d1) horizontal stress (advances 120m) (d2) vertiacl stress (advances 120m)

Fig.5 Stress diagram of coal pillar during the process of 4102 working face propulsion

4.3 Determination of the width of coal pillars

According to the principle of coal pillar retention, the width of the coal pillar is composed of the width of the elastic core in the middle and the width of the plastic zone on both sides. When the width of the elastic core is greater than or equal to 2 times, the coal pillar can remain stable.

In summary, it is recommended that the coal pillars have a width of 35 m, and there is an elastic core with a width of more than 2 times and a coal seam height of 4.8 m and a depth of 9.6 m, and a certain margin is left.

5. Conclusion

It can be concluded from the measured data: the lateral bearing pressure of the section coal pillar increases with the advancement of the working face, and its distribution shows the form of double peaks and one valley. After theoretical analysis of plastic deformation on both sides of the coal pillar, there exists a certain width of elastic nuclear zone in the center of the coal pillar, and the coal pillars are the law of approximate analysis with the measured data is obtained by numerical simulation analysis (double peaks and one valley). Therefore,

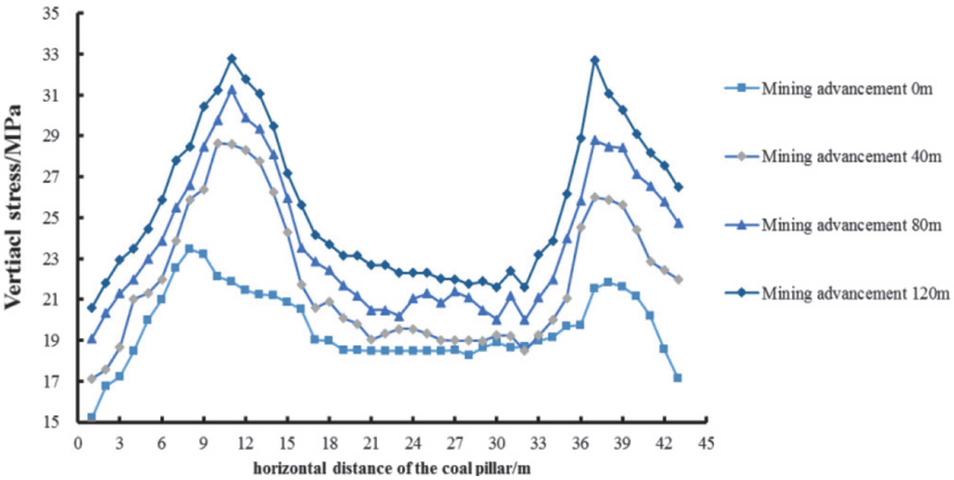


Fig.6 Vertical stress distribution curve of coal pillar during 4102 working face propulsion

the return air side coal pillar of the 4103 working face can be appropriately reduced.

Through theoretical calculation, numerical simulation, field measurement and analysis of the stress distribution law in thick coal seam coal pillar, considering the efficiency of coal recovery, the safety of coal pillar and the convenience of site construction, it is suggested that the width of coal pillar should be 35 m.

After determining the size of the coal pillar, the research results can be combined to provide a theoretical basis and reference value for the reasonable retention of coal pillars in thick coal seams under other similar conditions.

6. Acknowledgements

This paper is supported by “Priority Academic Program Development of Jiangsu Higher Education Institutions,” and “the Fundamental Research Funds for the Central Universities (2017XKQY044)”.

7. References

1 Wilson A.N. (1972): An Hypothesis Concerning Pillar Stability. *The Mining Engineer*. No.6.

2 Krauland N, Soder P. E (1987): Determining pillar strength from pillar failure observation, *Engrg. Min. J.* August.

3 Zhu Ling, Yan Shaohong (2011): Numerical simulation study on top coal migration law of large mining height fully mechanized top coal caving [J]. *Coal Mining,* 01:11-13+40

4 Bai Zhifei (2012): Study on the law of mine pressure behavior and surrounding rock control technology in large mining height fully mechanized caving face[D]. *Taiyuan University of Technology.*

5 Li Dongsheng, Li Dehai, Song Changsheng (2003): Modified application of limit equilibrium theory in strip coal pillar design [J]; *Journal of Liaoning Technical University*; 2003-01.

6 Jia Guangsheng, Kang Lijun (2002): Study on the stability of coal pillars in mining roadways for fully mechanized caving mining [J]. *Journal of China Coal Society,* 27(1): 7~10.

7 Zou Youfeng, Chai Huabin (2006): Research Status and Existing Problems of Stability of Strip Coal Pillars in China [J]; *Journal of Mining and Safety Engineering;* 2006-02.