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Analysis of stability of coal pillars with multi-coal seam strip mining

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Abstract: Strip mining is one of the efficient measures to control surface subsidence and mining damage. However, the researches on the laws of the geological mining factors to upper and lower pillar's stability are still deficient in multi-coal seam strip mining at present. Based on the three dimension fast Lagrangian analysis of continua (short for FLAC3D) numerical simulation software, the laws of the stress increasing coefficient on the coal pillar and its stability were systematically studied for different depths, different mining widths, different interlayer spacings, different mining thicknesses, different properties of interstratified rock and the spacial relations of the upper and lower pillars in vertical alignment in multi-coal seam strip mining. The function relation between the stress increasing coefficient of upper and lower pillars with the mining depth, mining widths, interlayer spacing, mining thickness, property of interstratified rock and the spatial relationship were obtained.

Key words: multi-coal seam strip mining; FLAC3D; numerical simulation; stability of coal pillar

1 Introduction

The coal accounts for about 70% in our country primary energy consumption. With a large number of coal resource exploiting from underground, the problem of surface subsidence and environment disaster caused by mining are becoming increasingly obvious. The main problem of mining subsidence subject is to exploit coal resource furthest at present [1] on the premise of protecting the buildings on the ground in security. The key problem of mining under the buildings is to control the rock strata and surface subsidence, which is one of the directions of mine subsidence [2]. Until now, there are many ways to control the movement of rock strata and surface, for example: backfill mining, partial mining, grouting cement to separated layer in overlying strata and so on. In spite of low rate of resource extraction in strip mining, it has been used extensively in mining area in China [3] because of its advantages including effectively controlling the subsidence of overlying strata and surface, protecting building and ecological environment, being convenient for safety in production and simple management and low cost.

Despite domestic and foreign scholars had a great deal of work and a plenty of academic and practical achievements are derived from strip mining, most of them are aimed at single coal seam [4−6]. Recently, the research and application on multi-coal strip mining have become more year by year [7−11]. However, in the light of design and practice of the multi-coal seam strip mining [12−15], there exist some deficiencies: 1) There are few studies on the factors effecting on the laying out strips in multi-coal seam mining, coal pillars stability and surface displacement; 2) the study of impact on rock mass and the upper and lower pillars' stability is less while layer between the multi-coal seams exist stress. 3) the researches on optimizing the designed theory of multi-coal seam strip mining and laying out the position of strip mining coal seams are not perfect. Based on the numerical simulation software, the laws of the coal pillar's stability was systemic studied for the different depth, different mining widths, different interlayer spacing, different mining thickness, property of interstratified rock and the special relations of the upper and lower pillar in vertical alignment direction in multi-coal seam strip mining in this paper. The function relation between the stress increasing coefficient of upper and lower coal pillars with the five factors were obtained.

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2 Model construction and project design

2.1 Numerical simulation model and boundary condition

The effect of coal pillar's stability of multi-coal seam strip mining was numerically simulated by using Three Dimension Fast Lagrangian Analysis of Continua (short for FLAC3D) software in this paper [16] under the conditions of the different depth, different mining widths, different interlayer spacing, property of interstratified rock and the special relations of the upper and lower pillars in vertical direction in multi-coal seams strip mining. According to the above aim of simulation, different models were constructed. The models adopt displacement boundary condition, applying horizontal displacement restriction in the front, back and left, right; the bottom of models restrict vertical and horizontal displacement; the top of the models are free boundary. In the process of computing and analyzing, the stress caused by its gravity is only considered, which is at the hydrostatic stress state and doesn't take into account of the effect of tectonic stress on in-situ stress. The initial stress state in the rock mass depends on the weight and property of overlying strata.

The aim of this simulation is to discuss the regularity, so the comprehensive geological histogram of certain mine is simplified: the coal seam floor is sandy mudstone with 40 m high; the thickness of coal seam is 3m; the strata height between the upper and lower coal seam is 30 m; immediate roof of mudstone's thickness is 16 m; the height of main roof of gritstone, siltstone and mild sandstone is 24 m and 60 m respectively; quaternary alluvium is about 20 m thick. In order to make sure the surficial supercritical mining, the mining district of numerical simulation model is 200 m by 400 m. For the sake of avoiding boundary condition effect, the dimension of designing model is 1 200 by 1 000 s by 286. Strike, orientation and vertical direction have different grid partitions, between 5 m to 40 m; each model has about 35 882 grid. According to the mechanical characteristics, Mohr-Coulomb yield criterion is applied on the models. In the light of field condition, the simulation parameters are listed in Table 1.

2.2 Numerical simulation project

This simulation is under the condition of upper and lower pillars in alignment and completely staggers and the extraction rate is 50%. The laws of the coal pillar's stability were systemic studied for the different depths, different mining widths, different interlayer spacings, different mining thicknesses, different properties of interstratified rock. Based on mining depth 200 m, approximately horizontal coal seam thickness 3 m, the interlayer spacing between the upper and lower coal seam 30 m and mining width 20 m, each simulation only has one parameter changing, for example, depth varying from 200 m to 500 m; mining width from 20 m to 50 m; interlayer spacing between the upper and lower coal seam from 10 m to 50 m; mining thickness from 1 m to 5 m; property of interstratified rock between coal seams from 0.25 to 2 times of in-situ stress.

3 Analysis of coal pillar's stability

Taking the case of middle coal pillar to analyse, on the upper and lower pillars with the law of distribution, under the condition of upper and lower pillars in alignment and completely stagger, the distribution of major principal stress on the coal pillar is simulated for different depth, different mining widths, different interlayer spacing, different mining thicknesses, different property of interstratified rock. Combining state map of major principal distribution of it, the stability of coal pillars can be made.

Define the ratio of major principal stress with in-situ stress as stress increasing coefficient of pillar, expressing with s (meaning of other parameters can be seen in integrated expression), which represents stress relative to in-situ stress on the coal pillar after strip mining pillars.

3.1 Effect of mining width on distribution on upper and lower coal pillar

The function relationship among major principal stress increasing coefficient of upper coal pillar with

Table 1 Rock parameters of simulation model

Strata	Bulk modulus/ GPa	Shear modulus/ GPa	Cohesion/ MPa	Angle of friction/ (°)	Tensile strength/ MPa
alluvium	0.002	0.000 4	0.01	20	0
Mudstone/Sandstone	0.880	0.190 0	1.50	33	1.0
Siltstone	0.830	0.470 0	6.25	33	2.6
Main roof	0.740	0.510 0	8.56	37	3.0
Immediate roof	0.130	0.040 0	1.50	32	1.0
Coal seam	0.210	0.040 0	1.00	25	0.1
Coal seam floor	0.690	0.520 0	24.60	38	3.0

mining width as follows.

In alignment:

$$S=1.1329\ln b-0.975,\ R^2=0.9451 \tag{1}$$

Completely stagger:

$$S=1.2915\ln b-1.4571,\ R^2=0.9618 \tag{2}$$

where R is correlation coefficient.

The function relationship between major principal stress increasing coefficient of lower coal pillar and mining width are as follows.

In alignment:

$$S=0.0939\ln b-0.0815,\ R^2=0.9752 \tag{3}$$

Completely stagger:

$$S=0.1173\ln b-0.7834,\ R^2=0.9368 \tag{4}$$

By comprehensive analyzing from Table 2 to Figs. 1−4, we can obtain: the stress increasing coefficient of

Table 2 Value of principal stress in upper and lower coal pillar

State	Mining width/m	Upper coal pillar's principal stress			Lower coal pillar's principal stress/MPa		
		Maximum/MPa	In-situ stress/MPa	Ratio of stress	Maximum/MPa	In-situ stress/MPa	Ratio of stress
In alignment	20	15.6	4.8	3.250 000	10.9	5.77	1.889 08
	30	20.2	4.8	4.208 333	14.4	5.77	2.495 67
	40	21.0	4.8	4.375 000	22.4	5.77	3.882 15
	50	22.5	4.8	4.687 500	26.3	5.77	4.558 06
Completely stagger	20	15.5	4.8	3.229 167	10.9	5.77	1.889 08
	30	20.6	4.8	4.291 667	12.5	5.77	2.166 38
	40	21.5	4.8	4.479 167	23.5	5.77	4.072 79
	50	23.8	4.8	4.958 333	29.8	5.77	5.164 64

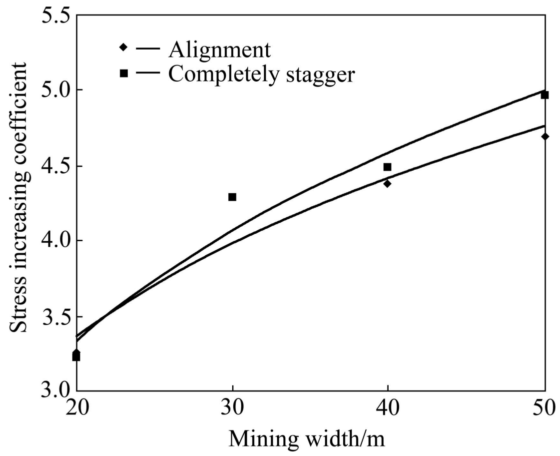

Fig. 1 Relationships between mining width and major principal stress of upper coal pillar (in alignment or not)

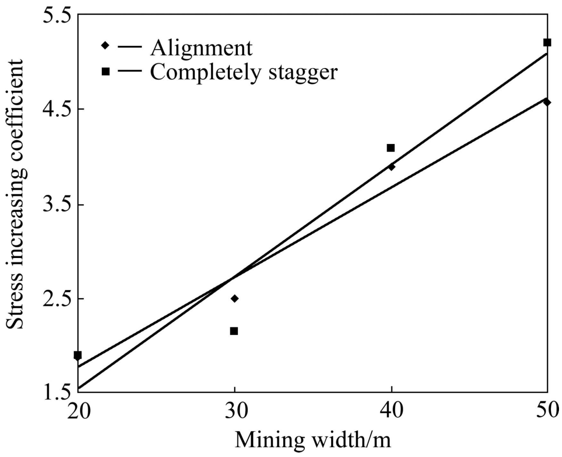

Fig. 2 Relationships between mining width and major principal stress of lower coal pillar (in alignment or not)

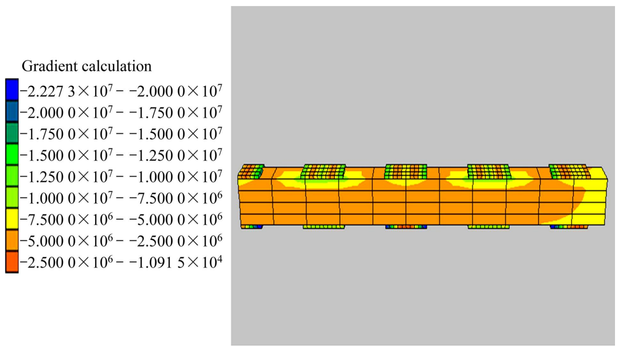

Fig. 3 Principal stress map of partial coal pillars and interlayer spacing rock in 50 m mining width (in alignment)

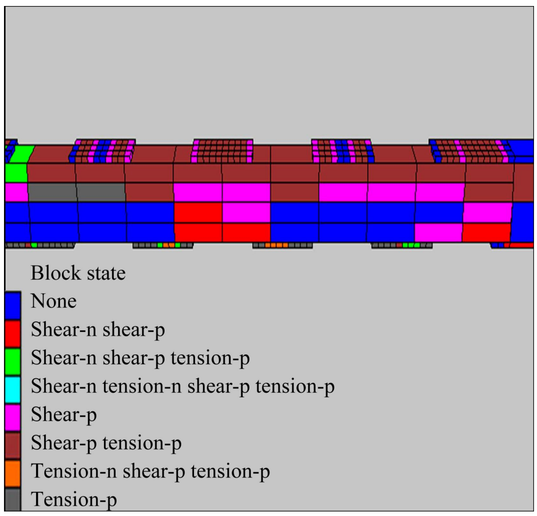

Fig. 4 State map of partial coal pillars and interlayer spacing rock in 50 m mining width (not in alignment)

upper coal pillar increases logarithm with the growing of mining width and the stress increasing coefficient of lower coal pillar increases linearly with it. As for the upper pillar, the degree of alignment has little effect on the ratio of stress with 20 m and 30 m mining width, however, when it is larger than or equal to 40 m, the stress increasing coefficient of alignment is greater than that of completely stagger state. The stress increasing coefficient of upper pillar is larger than that of lower one with 20 m and 30 m mining width whether alignment or not. However, when the mining width reaches 40 m or 50 m, the changing of stress increasing coefficient reverses to 20 m and 30 m. Because of the small width, the collapse height of interlayer rock doesn't impact on the stability of upper pillar causing by mining the lower coal seam and it forms press arch, which makes the stress of lower pillar become small. Whereas, when the mining width is larger than 30 m, the collapse height of lower goaf interconnects with concentrated force of upper coal seam floor, which makes upper pillar broken completely and there is no stable press arch between upper and lower coal seams, which causes the principal stress of lower pillar increasingly. The contour map of principal stress and state map reflect this kind of trend. So, as for this geology condition of mine area, the spatial relationship between upper and lower coal pillars doesn't need to be taken into account when the mining width is 20 m or 30 m, however, this relationship must be considered when mining width is larger than or equal to 40 m.

3.2 Effect of interlayer spacing on distribution on upper and lower coal pillar

Because of the length limitation, the analysis of the following four factors doesn't enumerate illustrations in detail and only present corresponding function expression.

The function relationship among major principal stress increasing coefficient of upper coal pillar with interlayer spacing (h) are as follows.

In alignment:

$$S=0.2554\ln h+3.28,\ R^2=0.9899 \tag{5}$$

Completely stagger:

$$S=-0.2966\ln h+5.4754,\ R^2=0.9771 \tag{6}$$

The function relationship between major principal stress increasing coefficient of lower coal pillar and interlayer spacing are as follows.

In alignment:

$$S=0.2805\ln h+2.8448,\ R^2=0.9778 \tag{7}$$

Completely stagger:

$$S=-0.4089\ln h+5.4726,\ R^2=0.9274 \tag{8}$$

When the upper and lower coal pillars are in vertical alignment and completely stagger, the stress increasing coefficient of upper coal pillar with the interlayer spacing are in form of logarithm. As for upper pillar, stress increasing coefficient raises with the growing of the interlayer spacing when pillars are in alignment; but when pillars are completely stagger, this variation reverses and both of them tend to a stable value with the increasing of interlayer spacing. The stress of the pillar in alignment is larger than that of pillar in completely stagger state, especially 10 m of interlayer spacing. Moreover, when the distance becomes large (40 m and 50 m), both of the stress on the pillar is approximately equal. As for lower pillar, principal stress increases with the raising of the interlayer spacing whether the upper and lower pillars are in alignment or not and under the corresponding condition, the ratio of stress on upper pillar is larger than that on lower. So, when the interlayer spacing is small (10 m or 20 m), upper and lower pillars should be in alignment in order to assure the pillar's stability; however, when that distance is larger, the alignment has little effect on the pillar's stability. The contour map of principal stress and state map, they show that both sides of coal pillars appear large-scale broken and the middle strip pillar exists central zone. Moreover, the interstratified rock collapses completely and in the middle of upper goaf forms trapezoid collapse zone. The central zone of coal pillar increases with the raising of interlayer spacing and tends to be stable increasingly, at the same time, high press zone and collapse width above the goaf become smaller.

3.3 Effect of mining thickness on distribution on upper and lower coal pillar

The function relationship between major principal stress increasing coefficient of upper coal pillar and mining thickness (m) are as follows.

In alignment:

$$S=-1.2173\ln m+5.5197,\ R^2=0.9991 \tag{9}$$

Completely stagger:

$$S=-1.2272\ln m+5.8043,\ R^2=0.9999 \tag{10}$$

The function relationship between major principal stress increasing coefficient of lower coal pillar and mining thickness are as follows.

In alignment:

$$S=-1.0776\ln m+4.9965,\ R^2=0.9998 \tag{11}$$

Completely stagger:

$$S=-1.1435\ln m+5.2803,\ R^2=0.9997 \tag{12}$$

When the upper and lower coal pillars are in vertical alignment or not, the stress increasing coefficient of upper coal pillar decreases logarithm with increasing of mining thickness and the trend of all curves is similar. The stress increasing coefficient of coal pillars in alignment is smaller than that of corresponding stress of completely stagger. From the contour map of principal stress and state map, they show that the effect height of interlayer rock mass becomes great and forms stable arch with increasing of mining thickness. Furthermore, there are little variation of the broken area of upper and lower pillars and exploiting lower coal seam has little effect on upper pillars. When the mining thickness increases, the broken height of interlayer rock body raises and the broken area on upper pillar grow slightly, meanwhile, the stability of coal pillars becomes worse and mining lower coal seam has impact on upper pillars' stability. When the upper and lower pillars are completely stagger, the broken height grows with the increasing of mining thickness. Comparing with alignment, the broken zone is larger. In the wake of mining thickness increasing, the collapse caused by lower goaf has effect on the coal seam floor of upper pillar and its stability. To sum up, the upper pillar's stability decreases with the raising of mining thickness.

3.4 Effect of mining depth on distribution on upper and lower coal pillar

The function relationship between major principal stress increasing coefficient of upper coal pillar and mining depth (H) are as follows.

In alignment:

$$S=0.0033H+2.4726,\ R^2=0.8623 \tag{13}$$

Completely stagger:

$$S=0.005H+3.0825,\ R^2=0.4182 \tag{14}$$

The function relationship between major principal stress increasing coefficient of lower coal pillar and mining depth are as follows.

In alignment:

$$S=0.0076H+0.3675,\ R^2=0.9367 \tag{15}$$

Completely stagger:

$$S=0.0104H-0.3096,\ R^2=0.9632 \tag{16}$$

When the upper and lower coal pillars are in vertical alignment and completely stagger, the stress increasing coefficient of upper and lower coal pillars increase linearly with growing of mining depth. When the mining depth is 200 m and 300 m, the stress increasing coefficient of upper coal pillar is larger than that of lower pillar and the spatial relationship between upper and lower pillars has slight effect on principal stress. Moreover, after extracting lower coal seam, the collapse height impact upper coal pillar slightly and press arch forms in the interlayer rock body, so the upper pillars are in stability; when the mining depth reaches 400 m and 500 m, the stress increasing coefficient of lower coal pillar is larger than that of upper pillar, except that, the broken of lower pillar and the collapse of interlayer rock mass influence the stability of upper pillar, which makes the stress of pillars increase rapidly, furthermore, this trend is faster with up and low pillars in alignment than that in completely stagger state. From the contour map of principal stress and state map, they present the stress of upper and lower pillars and interlayer rock body get bigger, the collapse of roof and floor of goaf become serious and there is almost no central zone when the mining depth is 400 m or 500 m. Because of growing of mining depth, even if the interlay rock mass are integrity, the stability of coal pillars would be impacted. When the upper and lower pillars are completely stagger, the situation of 200 m and 300 m depth is similar, however, the broken area is higher by reason of exploiting lower coal seam and concentrated stress of upper coal seam floor when mining depth reaches 400 m and 500 m, which bring the upper pillar completely unstable and lower pillar reserve small part of stable zone. Thus, as for this mine area, the layout of upper and lower pillars should be considered whether pillars are in alignment or not while the mining depth is greater than 300 m.

3.5 Effect of lithology between coal seams on distribution on upper and lower coal pillar

The function relationship among major principal stress increasing coefficient of upper coal pillar with lithology (E) between coal seams are as follows.

In alignment:

$$S=39.202E^{-0.115\,8},\ R^2=0.9873 \tag{17}$$

Completely stagger:

$$S=33.117E^{-0.11},\ R^2=0.9704 \tag{18}$$

The function relationship among major principal stress increasing coefficient of lower coal pillar with lithology between coal seams are as follows.

In alignment:

$$S=89.438E^{-0.168\,8},\ R^2=0.9998 \tag{19}$$

Completely stagger:

$$S=135.4E^{-0.188},\ R^2=0.9991 \tag{20}$$

When the upper and lower coal pillars are in vertical alignment and completely stagger, the stress increasing coefficient of upper and lower coal pillar decreases with increasing of property of interlayer rock. Under the same condition, the stress increasing coefficient of upper pillar is greater than that of lower pillars when pillars in alignment and the ratio of stress of pillars in completely stagger state is larger that of in alignment. As for upper pillar, with the increasing of property of interstratified rock, the major principal stress of upper pillar tends to be stable, however, that of lower pillars doesn't obviously express this kind of trend. From the contour map of principal stress and state map, they represent in the wake of lithology weak, the stress of interstratified rock gets small and the central zone of upper and lower pillars increases whether the upper and lower in alignment or not, whereas, the major principal stress of pillars raise, which show in the course of variation of lithology, the mining of lower coal seam impacts slightly on the stability of entire upper coal pillars.

3.6 Comprehensive expression of stress increasing coefficient of coal pillar

From above analysis, the function relationship between stress increasing coefficient with depth (*H*), mining widths (*b*), interlayer spacing (*h*), mining thickness(*M*), property of interstratified rock (*E*) are known.

Comprehensive expression of stress increasing coefficient of upper pillar in alignment by multiple regression analysis is

$$S=-4.1919+\ln\left(\frac{h^{0.05831}\cdot b^{1.69338}}{m^{1.2551}}\right)+38.41997E^{-0.11}-0.006025H,$$

R^2=0.9259 (21)

Comprehensive expression of stress increasing coefficient of upper pillar in completely stagger state is

$$S=-3.41681+\ln\left(\frac{b^{1.99445}}{h^{0.53768}\cdot m^{1.26489}}\right)+44.3321E^{-0.1158}-0.004326H,$$

R^2=0.90895 (22)

Comprehensive expression of stress increasing coefficient of lower pillar in alignment is:

$$S=-0.281960-(\ln h^{0.407649}\cdot m^{1.20376})+109.4735E^{-0.1688}+0.08733b-0.003895H,$$

R^2=0.71250 (23)

Comprehensive expression of stress increasing coefficient of lower pillar in completely stagger state is:

$$S=1.5171-(\ln(h^{1.11664}\cdot m^{1.2585}))+159.9639E^{-0.188}+0.108231b-0.0029478H,$$

R^2=0.7836 (24)

4 Conclusions

1) The stress increasing coefficient of pillars grows with increasing of mining width and depth. As for the geology condition of this mine area, the spatial relationship between upper and lower pillars doesn't need to be taken into account when mining width reaches 20 m and 30 m, however, when it is equal or larger than 40 m or the mining depth is greater than 300 m, the alignment of upper and lower pillars must be considered.

2) The stress increasing coefficient grows with the raising of interlayer spacing when pillars are in alignment and when they are completely stagger, the changing reverse, moreover, the stress increasing coefficient tends to be stable value with the increasing of interlayer spacing. As for this mine, 30 m thickness is a threshold.

3) Contrasting the distribution law of major principal stress on upper coal pillar with that of lower pillar, the lower stress is larger than upper's at last and the law is opposite when the mining thickness or property of interstratified rock changes.

4) The function relation between the stress increasing coefficient of upper and lower pillars with the five factors in alignment and completely stagger state.

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