Dynamic Evolution Law and Width Determination of Section Coal Pillars in Deep Mining Height Working Face

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Abstract

The coal column undergoes three types of force evolution from the formation to the end of mining. This paper takes large mining height working face at No.2 Coal Mine as example to study the ways to avoid dynamic instability of the coal column triggered by the deep mining. By means of geological survey, theoretical analysis, numerical calculation and field verification, the load processes under the three stress stage are proposed, and the evolution law of the coal column is analyzed. The study shows that the depth, large mining height working face, coal pillar force and size altogether determine the damage characteristics of the coal pillar. With the combination of Flac3D and 3DEC, it can be analyzed that the plastic failure and displacement characteristics of the 35m coal column under the action of secondary dynamic load coincide. The perturbation stress distribution is stable, which finally determines the reasonable width of the 35m coal column. Field measurements show that the top and gang of the 35m coal column undergo three kinds of displacement characteristics. The lower part is more stable. The top plate of the upper and lower corner completely collapsed in the emptying area, which can play a good supporting role.

1. Introduction

As a part of the "coal-rock" system, coal pillars are the basis of roadway distributions. The formation of coal pillars and the changes in working faces are disturbed by static and dynamic loads of varying degrees, resulting in problems that appear in mine pressures, such as large deformations of the two sides of coal pillar, serious heaving floors of roadways, etc. Deep and super-long advancing distances resulted in long stress times in mining faces and further increased the weighting intensity of working faces with large mining heights. Therefore, to research the evolutionary characteristics of "static-dynamic" loads of coal pillars on working faces with super long, deep, and large mining heights consisting of realistic necessities for the layout of goaf-side roadways and preventing coal pillar dynamic instabilities.

According to different coal pillar functions, they are primarily divided into four categories^[1]. Coal pillar stability on deep working faces is different from that of medium-shallow buried coal pillars with large dip angles and steep dips^[2-5]. Under coal pillar loading, the loading rate determines fracture toughness and fracture surface roughness for coal pillars and changes the critical strain energy of unstable fracture propagation of coal pillars. Under different loads, the additional horizontal stresses caused by primary defects of coal samples are greater than the macro damage of the roof-pillar structure caused by coal sample tensile strengths^[6-9]. Through slight shocks, it has been found, influenced by dynamic pressure, the strength of the fault protection of coal pillars itself is low, the stresses in the fault area are concentrated, and the stresses in the rock mass have adjusted, resulting in a large number of micro fractures in the rock mass and causing an increase in micro seism activity rates^[10-11]. With the increase in coal pillar width, roadway deformation presents a change of initially increasing, then decreasing, showing obvious asymmetrical characteristics and regional distributions^[12], and finally a method to detect the impact risks of mining roadways jointly by slight shock and CT^[13-14] has been formed. As for

narrow coal pillars, through the tectonic stresses of crustal stress inversion, it has been found that the vertical stress distribution on coal pillars at the symmetrical positions of fold backs and syncline centers has "respectively similar" features, and these features increase with the coal pillar width^[15]; the support scheme for the goaf-side roadway of the fully mechanized caving face of "high-strength anchor bolts for support + a composite structure for roof anchor cables interlocked by channel steel + coal pillar side reinforced with anchor cables" was put forward and applied on site^[16]. Deep mining has caused a complex mechanical environment of "high crustal stresses, high ground temperatures, high permeation pressures, and strong mining disturbances"; and the evolutionary characteristics of engineering disasters^[17–21]. Focusing on deep dynamic disaster prevention and by taking measures on numerical calculations, theoretical analyses, field tests, and other means, the Deep Dynamic Disaster Prevention Team at the Xi'an University of Science and Technology has researched on the characteristics of "three factors" (dynamic hazard energy source, outstanding medium, and inducing conditions) of dynamic disasters occurring under disturbances of deep extra-thick coal seams, roof fracture, overburden movement, and "roof-coal seam-floor" disturbance stress propagation etc. and has successively proposed technologies, such as deep hole pressure releases, coupling pressure releases, etc., thus weakening the occurrence of dynamic disasters from the source^[22–29].

The theoretical and practical research on coal pillar dynamic disasters has strongly supported the safe and efficient mining, but little relevant research has been conducted on layout methods for goaf-side roadways of mining faces with overlength at deep and large mining heights. The authors have been committed to researching dynamic disasters for a long time^[30–31] and have fully drawn on previous research experiences and achievements. Focusing on the working faces with an overlength at deep and large mining heights at No.2 Coal Mine of Huangling Mining (Group) in Shaanxi Province, the authors have researched the "dynamic-static" load evolution rules for coal pillars, and ultimately determined the layout method for goaf-side roadways, thus providing a scientific basis of safe, efficient and sustainable mining in the stopswith large mining heights at deep.

2. Geotechnical Overview

2.1 Occurrence Characteristics of Coal Seams

No.2 Coal Mine of Huangling Mining (Group) is located in the middle of Huanglong Mining Area, an administrative division which belongs to Shuanglong Town, Huangling County, Yan'an City, Shaanxi Province, China. It is the main production mine for coal bases, having excavated 1.4 billion tons in the first batch with a production capacity of 8.0Mt/a. In this mine, the #2 coal seam has been the focus of mining. It belongs to the Yan'an Formation of the Middle Jurassic System with dip angles of 1–5° generally. This coal seam is stable to relatively stable. The #2 coal seam is divided into 10 panels, four of which are located northwest of the mine field, with surface elevations of + 1,157 to + 1,423m and underground elevations of + 711 to + 732m, average buried depth about 570m, average mining height of

6.0m, and original rock stress of about 12.53MPa. The overburden within 100m of the coal seam in the four panels is stacked with siltstone and fine sandstone, as shown in Fig. 1.

2.2 Mining Layout

The mine is divided into several panels, of which the coal seams of the four panels are currently single-wing mining, and 20 working faces are planned to form a large mining height working face group. From October 2018 to December 2019, the 418 working face was mined. The working faces change along the development direction of the main roadway, increasing disturbance spaces of the working faces. Each working face is arranged with 3 roadways (auxiliary haulage roadway, belt conveyor roadway, and return airway). The auxiliary haulage roadway for the working face serves as the return airway for the next working face, as shown in Fig. 2. The coal seam has a weak impact tendency, and the working face roof has an impact tendency.

The method of One Draw Back mining at the full height of the coal seam along the strike longwall has been adopted at the working face, and the all-caving method has been used to dispose goaf from the roof. The advancing length of the working face is about 3,000m, and the width is about 300m, a total of 175 supports have been arranged. On average, 11 knives of coal advance each day, and 0.9m of coal is cut with one knife. Section coal pillars (L) are reserved between the two working faces. The intake airway and air return roadways are rectangular with sizes of 4.6m × 3.8m, 5.4m × 3.6m respectively. The combined support of anchor bolt-anchor cables has been adopted.

2.3 Caving Characteristics and Mining Stress Environments

After the working face with overlength at deep and large mining height was stoped, the typical disturbance characteristics in time, range and strength, namely long time of force-bearing, wide disturbance ranges and strong mining-induced stresses were formed. As shown in Fig. 3, when the coal pillar of the deep coal seam formed, it was subject to the uniform distribution load of the overlying strata and the lateral stresses from the roadway, thus forming the static load (δ_q) of the coal pillar; stoping at the working faces on both sides of the coal pillar intensified the magnitude and range of disturbance stresses and acts on the coal pillar, thus forming the dynamic load (δ_d) of the coal pillar. With changes in working faces, enlargement in dynamic loads and increases in disturbance ranges, the secondary dynamic load (δ_{d2}) of the coal pillar formed.

According to the rock strata control theory, the supporting stresses (δ_q) on both sides of the coal pillar at stops with large mining heights migrate to the inside of the coal pillar as the width L of the coal pillar decreases, as shown in Fig. 3(a). When the width of the coal pillar decreases to L', the lateral stresses overlap inside the coal pillar. The decreasing of the coal pillar causes the supporting stress of the coal side to exceed the ultimate strength of the coal body, thus the fracture area (deformations, side collapses) with certain width forms.

The motion features of overlying rock after the 416 working face was stoped are shown in Fig. 3(b). Along the broken short-lines of the 416 rock formations, the disturbance ranges and energy of lateral support stresses for each rock formation increased. Disturbance stresses (δ_{d1}) of coal pillars migrated to the interior, and stress peaks and elastic-plastic zone ranges increased; coal pillar disturbance ranges and values at the side of the 418 working face increased correspondingly. When the coal pillars reduced to L' , disturbance stresses on both sides of the coal pillar increased and superimposed, resulting in the emerging phenomena of dynamic disasters, such as sudden stress releases on the coal pillar on the side of the 416 working face, serious heaving on the walls on the side of the 418 working face and caving were prone to occur along roadways prematurely.

The 418 working face was mined along the goaf, so that the overburdened strata would have a large area to move. The formation of lateral support forces acted upon the coal pillar and the 420 working face. Under the conditions of stops with mining heights at deep and along goafs, high-level fissure development results in the rock layers acting on spatial structures dominated by "top plate-coal pillar (body)-bottom plates" (see Fig. 3(c)). The disturbance stresses inside the coal pillars increased as a whole. As the coal pillar decreased to L' , stress and energy gathered within them, and the elastic zone in the middle of the coal pillar transformed into the plastic zone, then the stress released from the coal pillar in the working face slowly transferred from the energy accumulating inside the coal pillar to the periphery of the roadway and converted into a sudden release of high stress inside the coal pillar, which caused the roadway to arc and crack, causing anchor cables to fall off and the roadways on the coal pillar side and roof to prematurely cave in. Thus, dynamic instability is prone to occur on the "roof-coal side", thus causing dynamic disasters to occur. From this, it can be observed that the roadway position of fully mechanized mining faces with overlength at deep, large mining heights, and long walls are determined by disturbances from jointly mining on the working faces on both sides of the coal pillar.

According to incomplete statistics, the phenomena of undercutting (cumulative thickness of 4.2-5m), coal pillar side collapses, anchor rod and anchor cable heads falling off have been dealt with 6 times during the service period for the auxiliary haulage roadway of the 416 working face (return airway of the 418 working face), as shown in Fig. 4.

(a) Flooring heaving (b) Undercutting height (c) Foot heaving (d) cracking

Figure 4. Emerging phenomena of mine pressure on both sides of coal pillar

3. Numerical Simulation

3.1 Design and Construction of Numerical Model

According to the occurrence of coal seams in four panels, with reference to the histogram of the 418 working face borehole and in combination with rock mechanic calculation advantages of Itasca

Company's finite difference method (FLAC3D) and discrete element method (3DEC) and by importing in CAD graphics, the numerical calculation model shown in Fig. 5 was established.

The size of the Flac3D large-scale three-dimensional calculation model is 900m × 180m × 800m (length × width × height), and two working faces are provided, with coal pillars (L) in the middle. Slices are taken along 350m along Axis-Z to analyze plastic failures and stress distribution rules of coal pillars under "static-dynamic" loads. Using block chain, one 3DEC calculation model with the same size as the slice (the grids have been divided consistently) was established to analyze the motion features of each coal pillar under disturbance.

The downward force applied to the top of the model is 9.6MPa. The size of the division grid for coal seam is 1 m, and that of the roof and floor is 2m.

3.2 Constitutive Model and Physical and Mechanical Parameters

By changing the coal pillar size, five different calculation schemes were designed. According to the actual production situation, 416 working face and 418 working face were mined successively, and the evolutionary characteristics of 40m, 35m, 28m, 24m and 20m coal pillars were analyzed successively.

Table 1
Mechanical parameters of surrounding rock

Name	Volume Modulus (GPa)	Cut Modulus GPa	Tensile Strength MPa	Cohesive Force (MPa)	Internal Friction Angle (°)	Volume Weight (KN.m ⁻³)
Silt stone	7.35	5.03	6.80	5.72	26.5	2700
Fine sand stone	5.16	4.21	5.50	4.9	25	2650
Coarse sand stone	5.16	4.21	3.70	3.9	25	2550
Mudstone	4.32	3.67	2.7	3.1	25	2420
Coal	2.38	1.16	4	3.3	26.1	2000
Medium sand stone	4.32	3.67	4.6	5.1	25	2600

According to geotechnical data and the rock mechanic test results provided by relevant research, the rock mechanic parameters used in the simulation calculation calculated with Mohr-Coulomb criteria are shown in Table 1.

4. Evolution Characteristics Of Static Loads

4.1 Plastic Distribution Rules of Surrounding Rock

Plastic zones of coal pillars are an important index to evaluate coal pillar stability. Under static loads, the plastic failure ranges of coal pillars are fundamentally the same, as shown in Fig. 6.

Coal pillar failures are primarily shearing failures, and the failure ranges of the two sides of the coal pillars are constant $2\text{m} \times 5\text{m}$ (20m^2 in total), with symmetrical characteristics. As the coal pillar decreased, its area decreased, resulting in an increase in plastic ratios, and the plastic proportion of each coal pillar is shown in Table 2. The plastic failures of roadway roofs, floors, and sides are 2m, 4m and 2m respectively.

Table 2
Plastic failure ratios of coal pillars under static load

Coal Pillar Size/m	Coal Pillar Area/m ²	Damaged Area/m ²	Plastic Proportion/%
40	240	20	8.33
35	210	20	9.52
28	168	20	11.9
24	144	20	13.89
20	120	20	16.67

4.2 Disturbance Rules of Coal Pillar Stresses

The internal disturbance stress characteristics of 40-18m coal pillars under static load are symmetrical, as shown in Fig. 7. Stress concentrations of $1\text{m} \times 1\text{m}$ occur at about 2m to two sides of 40-18m coal pillars, with a stress peak value of about 18.38MPa. The disturbance stresses of 35m coal pillar roofs start to coincide, and the disturbance stresses of the 28m coal pillar roof completely coincide, with a stress value of about 13.05MPa.

4.3 Displacement Characteristics of Coal Pillars

Vertical displacements of coal pillars are fewer and roof settlements of roadways near the coal pillar side are the largest (about 0.464m), as shown in Fig. 8. Vertical displacements of coal pillars are symmetrical, and displacement characteristics of 40m to 28m coal pillars are fundamentally the same. When the width of the coal pillar is smaller than or equal to 24m, influence boundary angles of right roadways on coal pillars gradually decrease (56° to 43°), of which the included angle of 40m, 35m and 28m is always 58° . The influence boundary of the top of the left roadway on coal pillars remains the same, about 33° . Horizontal displacements of the two sides are shown in Fig. 9.

As the coal pillar shrinks, horizontal displacements of the two sides of each coal pillar is within 0.072m. The maximum and minimum displacements that change for the two sides are #1 point and #4 point respectively, and the evolutionary characteristics of the sides change from "convex" to "linear". It can be seen from this that after coal pillars in deep mine are formed, its disturbance stresses, displacements and plastic failures are caused by roadway excavation, and the deformation characteristics are symmetrical, and the deformation rules at the left and right sides are fundamentally the same. Roadway support on both coal pillar sides should be determined by influence.

5. Evolution Rules Of Dynamic Loads

5.1 Characteristics of Plastic Failures under Dynamic Loads

After the 416 working face and 418 working face on both sides of the coal pillars were mined in turn, disturbance stresses and rock strata movement ranges increased. Coal pillar plastic failure ranges, shapes, and characteristics formed by changes of mining faces are different, as shown below.

(1) Plastic Failure Characteristics in Mining of 416 Working Face

With decreases in coal pillars, plastic failure ranges of coal pillars increase and their shear failure ranges expand inwards, with plastic failures of "overhand mining" appearing at the sides of the 418 working face, as shown in Fig. 10.

Plastic failures of the two sides of 40m and 35m coal pillars are fundamentally the same. During are duction of 35-24m, plastic failures at the sides on the 416 working face increase by 1m and 2m inwards in turn, and the evolutionary characteristics of "overhand mining"appear at the sides of the 418 working face. Failures of the top and floor of the 28m coal pillar evolved to the unmined side and passed through the 24m coal pillar. After 24m coal pillars, plastic failures of the "overhand mining"disappear, plastic failures passed through within 1m of the bottom of the 20m coal pillar, and an undamaged area of 5m×5m (width × height) appeared inside the coal pillar.

Table 3
Plastic damage ratios of coal pillars under mining of 416 working face

Coal Pillar Size/m	Coal Pillar Area/m ²	Damage Area/m ²	Plastic Proportion/%
40	240	52	21.6
35	210	53	25.2
28	168	65	38.69
24	144	75	52.08
20	120	95	79.17

As shown in Table 3, firstly, as coal pillars decrease, the damage area increased, and the plastic proportion gradually increased. Secondly, the proportion of plastic increased by 1.5 during decreases of 35m to 20m coal pillars; the proportion of 35m plastic is 1.16 times that of 40m. Thirdly, the area of the 35m coal pillar reduced by 30m², and the failure area increased by 1m² when compared with 40m coal pillars, which indicates that 35m and 40m coal pillars can have the same supporting effect.

(2) Plastic failure characteristics of stoping at the 418 working face

After the working faces on both sides of the coal pillar were excavated, the range of influence of dynamic loading intensified, and the plastic failure range further expanded, as shown in Fig. 11. The 40-28m coal pillars have different plastic fracture characteristics and the coal pillars of 24m and below were completely destroyed.

Plastic failures of connectivity occurred initially within a 1m range of the top of 40m and 35m coal pillars, and then it occurred at 2m for the 28m coal pillar. Plastic failure boundaries on the left side of 40-28m coal pillars appeared on "overhand mining", and the number of steps decreased with coal pillar decreases. A symmetrical "trapezoidal" non-destructive stability structure formed inside the 35m coal pillar. After the 28m coal pillar, with decreases coal pillars, the entire coal pillars will be destroyed.

Table 4
Proportion of coal pillar plastic failures under mining of 418 working face

Coal Pillar Size/m	Coal Pillar Area/m ²	Damaged Area/m ²	Plastic Proportion/%
40	240	148	61.67
35	210	84	40
28	168	125	74.4
24	144	144	100
20	120	120	100

Plastic damage of coal pillars under mining of the 418 working face are shown in Table 4. The plastic proportion of 35m coal pillar is the smallest, and the plastic proportion of 24m and 20m coal pillars reached 100m.

5.2 Stress Distribution Rules for Coal Pillars

(1) Distribution characteristics of stoping stresses of the 416 working face

Affected by the triple influence of stoping of the 416 working face, coal pillar size, and overburdening, the evolutionary rules of vertical stresses of coal pillars and roofs are shown in Fig. 12.

Stress concentrations occurred at about 4m from the two sides of the coal pillar and did not change with coal pillar size changes. Under the joint influence of one-sided mining and roadway excavation

disturbance stresses, the stresses on the mining side are higher, and the roof stresses move towards the sides of the 418 working face. Decreases in coal pillars resulted in gradual decreasing of stress peak spacing between the two sides of the coal pillar, and the disturbance stresses of the coal pillar pass directly through the top at 20m, forming a stress "arch" structure. Mining on the working face greatly influenced the coal pillar. The evolutionary characteristics of coal pillar vertical stresses caused by mining at the 416 working face are shown in Fig. 13.

It can be observed from Fig. 14, firstly, the mining stress value at 4m of the coal side of 416(a) is the largest (about 30.5MPa) and does not change with changes in coal pillar size. The non-mining side of the 418 working face is affected by residual stresses of mining and roadways, the stress peak value increased linearly with decreases in coal pillars. Secondly, disturbance stresses of each working face show the evolutionary characteristic of "double peaks". The smaller the coal pillar size, the higher the symmetry of "double peaks". Thirdly, according to supporting stress boundaries (13.16MPa), coal pillars are all within the supporting stress range.

(2) Distribution characteristics of stopping stresses of the 418 working face

Mining at the 418 working face intensifies rock strata movement. Disturbance stresses of coal pillars and roof moves, and coal pillar stresses are concentrated at the junction with the floor, as shown in Fig. 14.

The stress distribution of the roofs of each coal pillar is symmetrical, and the disturbance stress value gradually increases with decreases in coal pillars, with a maximum stress peak value of 20m coal pillar (85.1MPa). Stress concentration occurs at 8m from each coal pillar to the left side, and stress values on the left side are greater than that on the right side. The distribution of disturbance stresses at 40m and 35m are similar. Stress concentrations of 28-20m coal pillars have overlapping trends. Under mining along the goaf, stress releases of different degrees occur at the two coal pillar sides. Mining along the goaf has the largest influence on coal pillars, evolutionary characteristics of vertical stresses of coal pillars after mining at the 418 working face are shown in Fig. 15.

As shown in Fig. 15, firstly, residual stresses acting on coal pillars in the goaf and disturbance stresses after mining in the alternating working face are superimposed, and disturbance stresses for the coal pillars of different sizes increased. Secondly, the stress peak appears at 8m away from the two sides of coal pillars. Thirdly, affected by the overlying strata of coal pillars, its size and mining range, stresses evolve from the "concave" distribution to the "V" distribution between peaks. Fourthly, the peak stress of the 40m coal pillars at the side of the 418 working face is 0.6MPa higher than that of the goaf-side, and the peak stresses of both sides of 35m coal pillars are fundamentally the same. The peak stresses of 28-20m coal pillars at the goaf-side (416 working face) are 0.57MPa, 0.97MPa, and 2.44 MPa higher than those of mining sides respectively. Fifthly, the stress peak value is 2.3–3.3 times the compressive strength of the coal block.

5.3 Displacement Rules for Coal Pillars

(1) Displacement characteristics of coal pillars under mining of the 416 working face

After the 416 working face was mined, the movement phenomenon of "pry plate" formed 10m from the left side and top of the coal pillar (the mining side is the "caving" plate), as shown in Fig. 16. The roadway roof at the side of the 418 working face sank, and the bulging phenomenon appeared. Reduction in coal pillar size leads to subsidence of the roadway roof and increases in wall bulging. The included angle between the "caving plate" and the horizontal level of each coal pillar is about 24–25°, and the "prying point" is about 10m away from the unilateral mining boundary (left side of the coal pillar). The lengths of the "stabilizing plate" of 40-18m coal pillars are 40m, 25m, 18m, 14m and 10m respectively. The roof of the 28m coal pillar began to bend, and the roof of the 24-18m coal pillar cracked.

The horizontal displacements of the two sides of coal pillars are shown in Fig. 17. Disturbances in the coal pillar side caused by mining are obviously large, as shown in Fig. 17 (a). The horizontal displacements of each monitoring point of coal pillars increase with decreases in coal pillars. The displacements of #1 monitoring points of each coal pillar is the largest and that of #4 monitoring points is the smallest. Horizontal movements of the left side of 40m and 35m coal pillars are relatively stable, with a difference of 0.1m. The horizontal displacements at the side of the 418 working face are shown in Fig. 17 (b). The detection points of coal pillars are within the range of 0.5m, and the horizontal displacement gradually increases with decreases in coal pillars, evolving from "convex" to "linear". Both sides of 35m coal pillars are in a "half arc".

(2) Displacement characteristics of coal pillars under mining of the 418 working face

After both sides of the coal pillar were mined, the overall displacement presents the characteristics of a "fan-like" distribution, and the interior of the coal pillar presents movement characteristics from "trapezoidal" to caving, as shown in Fig. 18.

The interiors of 40m, 35m and 28m coal pillars present "trapezoidal" movement characteristics. 45m and 35m coal pillars have fundamentally the same "trapezoidal" evolutionary characteristics, with the included angles on both sides of 28° and 22° respectively. The included angles on both sides of the 28m coal pillar are 25° and 35° respectively, and the upper roof of the coal pillar is bent. The "trapezoidal" movement characteristics of 24-18m disappeared, and staggered layers formed inside the coal pillar, thus triggering its overall subsidence. The upper roof of the coal pillar was broken, and with decreases in coal pillars, the fracture angle increases, which makes it easy to aggravate the dynamic instability of coal pillars.

After the two sides of the coal pillar and the roof of the roadway completely collapsed, the horizontal displacements from the two sides of the coal pillar were extracted, as shown in Fig. 19. The horizontal movements of the two sides of each pillar change linearly and have symmetrical characteristics, and the horizontal displacements at the #1 to #4 monitoring points decrease in turn. After disturbing along the goaf, the entire coal pillar was in a "fan-shaped" structure. The horizontal displacements at #1 and #4 monitoring points of coal walls at the side of the 416 working face is between 2.43.5m and between 1.65-

3.2m respectively. The horizontal displacements of #1 and #4 monitoring points of coal walls at the side of the 418 working face are between 1.7-3.2m and 1.4-2m respectively. From this, it can be observed that the migration amount of coal walls at the side of the 416 working face is greater than that of the 418 working face. The combination of coal pillars and tops are more likely to form dynamic disasters.

5.4 Width Determination of Section Coal Pillar

From the numerical simulation results, it was observed that, (1) the disturbances of coal pillars intensify after changing and stoping working faces. The coal pillars initially had plastic damage at the tops of coal pillars and a stable "trapezoidal" feature inside 35m coal pillars; when coal pillar sizes are smaller than or equal to 24m, plastic damage across the entire coal pillar occur. (2) Stress distribution evolves from "double peak" to "V", and stress peak values along the goaf-side are the largest. (3) The movements inside the coal pillar change from "pry plate type" to "fan-shape", and the movements inside the 40-28m coal pillar form "trapezoidal" characteristics. (4) Dynamic instability is more likely to occur when both sides of coal pillars in deep sections are sequentially stoped.

Therefore, the layout of the goaf-side roadway of the working face with overlength at deep and large mining heights should be determined according to changes in working faces. The distances between working faces are more than 28m, which can meet production demands for working faces with overlength at deep and large mining heights, of which 35m coal pillars possess the strongest stability. At the same time, due to the ups and downs of coal seam roofs and floors, it is difficult to maintain the "flat roofs, flat bottoms, flat coal walls, as well as straight coal walls" in the dynamic process of coal mining, and there is a need to expand the walls. Finally, it is determined that the layout of goaf-side roadways of working faces with overlength at deep and large mining heights should be 35m away from the previous working face.

6. Engineering Practices

6.1 Roadway Support Schemes

Through joint analysis of numerical calculations, roadway designs, and suspension theories, the roadways on both sides of coal pillars are supported by anchor bolt-anchor cables. The on-site support construction is shown in Fig. 20, and the support parameters for anchor bolts and anchor cables are shown in Table 5.

The arrangement of "one beam and five cables" was applied for roof anchor cables. For anchor cables on both sides, the edge-holding anchor cables were constructed on top. The side anchor bolts were complete, high-performance torque nut anchor rods. The pre-tightening force for anchor bolts and anchor cables were not less than 150KN and 260KN respectively. Anchor cable beams were T140 steel strip with specifications of T140-6, 400mm. They were tightly attached to the coal and rock surfaces. The specification of anchor cables was 400mm × 400mm × 12mm and that of the Q235 steel trays for anchor

cable was 200mm × 200mm × 12mm. The mesh was $\Phi 6.5$ -2,000mm × 1,000mm bar-mat reinforcements (with mesh opening of 100mm × 100mm), and the overlapping length among meshes was 100mm.

Table 5
Roadway support parameters

Name	Top				Side		
	Support Materials	Model	Spacing (m)	Row spacing (m)	Model	Spacing (m)	Row Spacing (m)
Auxiliary Haulage Roadway	Anchor Bolt	$\Phi 22 - 3,500\text{mm}$	0.8	0.8	$\Phi 22 - 3,500\text{mm}$	0.8	0.8
(Return Airway)	Anchor Cable	$\Phi 21.8 \times 8,300\text{mm}$	1.6	1.6	$\Phi 21.8 \times 8,300\text{mm}$	1	1.6
Belt Conveyor Roadway	Anchor Bolt	$\Phi 22 - 3,500\text{mm}$	0.8	0.8	$\Phi 22 - 3,500\text{mm}$	0.8	0.8
	Anchor Cable	$\Phi 21.8 \times 8,300\text{mm}$	1.6	1.6	$\Phi 21.8 \times 8,300\text{mm}$	1	1.6

6.2 Roadway Layout Schemes

The 416 working and 418 working faces are two adjacent parallel working faces. According to mining sequences of working faces, the 416 working face, and 418 working face were mined on July 2017 and October 2018 respectively, and a cross heading was designed every 500m or so. Surrounding rock was observed for #3 cross heading each working face, and the monitoring scheme is shown in Fig. 21.

The LBY-3 separation meter and BGK-A3 multipoint displacement meter are used for roofs and coal pillar sides respectively, and data collection starts when the working face is 200m away from the #4 cross heading. The effective monitoring range of LBY-3 separation meter is 0-300mm, and that of GK-A3 multipoint displacement meter is 0-500mm.

6.3 Effect Analysis of Roadway Layout Schemes

When the 416 working face and 418 working face are 200m away from the #4 cross heading, data collection starts, and the data is continuously monitored for 30 days, with a cumulative advancement of about 300m. After the 416 working face and 418 working face are mined, the displacements of roof and wall are shown in Fig. 22–23 (+ is taken from the push mining position to the #4 cross heading).

After the 416 working face is mined, the settlement characteristics of 3 different kinds of rates occurred at the roof on both sides of coal pillars, as shown in Fig. 22(a). The change rules for the #1 and #2 monitoring points are the same in Area-I and Area-II. The roof subsidence of 200-50m in Area-I increased linearly, and the settlement gradually increased to 25mm. The subsidence rates of the 50m – 0m roof in Area-II accelerated due to mining influences, and the subsidence ranges are between 25mm and 55m,

with an average growth rate of 0.6. The location of the working face in Area-III was 70m from the goaf, and the subsidence rates were the fastest (the subsidence rates were about 3.6); when the working face was 70m away from the goaf, the roof completely collapsed. Affected by the coal pillar, the variation rates of the #2 monitoring points near the coal pillar sides in Area-III were slightly slower than that of the #1 monitoring points. The variation rules for the #3 and #4 monitoring points are consistent, and there are no obvious settlement changes between 200m and 70m; the settlements of 70-30m roof are increased, with a maximum of 20mm and it tends to be stable. There is no obvious change in roof settlements from 30 to 100m.

Affected by mining of the 416 working face, the #1 and #2 monitoring failed (they will no longer be recorded). The subsidence characteristics of the #3 and #4 monitoring points after the 418 working face was stoped are similar to the variation characteristics of the #1 and #2 monitoring points after the 416 working face was stoped, as shown in Fig. 22(b). At 60m and – 10m away from the working face, the roof settlement in the goaf turns. The rates of change of the #4 monitoring points near coal pillars are quickest in Area III, and the two monitoring points completely collapsed at -50 and – 80m respectively.

(a) Settlement of mining roof at 416 working face (b) Settlement of mining roof at 418 working face

Figure 22. Settlement characteristics of roofs on both sides of 35m coal pillars

The roof on both sides of the coal pillars has passed three stages including "steadily increasing, increasing and rapidly increasing" in settlement. The roof of 60-70m working faces at the goaf has completely collapsed.

Stoping at the 416 working face resulted in different horizontal displacements at two sides of coal pillars, as shown in Fig. 23(a). The horizontal displacements on the left side (#5 and #6 monitoring points) of the coal pillars are divided into three areas. No displacement occurred at the #5 and #6 monitoring points of 200m-100m in Area-I. At the 100m working face position(0m), the horizontal displacements at the #5 and #6 monitoring positions increased linearly. At 100m from the working face to the goaf, the variation rates of horizontal displacements on the left side accelerated and reached the monitoring limit (500mm) at 100m from the goaf. The horizontal displacements of the upper part of coal pillars (#5 monitoring points) were slightly larger than that of the lower part of coal pillars. On the 416 working face, the horizontal displacements on the right side of coal pillars were caused to change from 0mm to 35mm and 33mm. No horizontal displacements occurred between 200mm and 70m on the side of the coal pillar on the 418 working face. The horizontal displacements from 70m to the goaf increased to the maximum, and no apparent changes were observed after 70m on the working side of the goaf.

(a) Displacements of mining two sides of 416 (b) Displacement of mining two sides of 418

Figure 23. Displacement characteristics of two sides of 35m coal pillars

In the process of advancing and mining at the 418 working face, the horizontal movements of the right side are intensified, and the disturbance positions advanced by about 10m, as shown in Fig. 23(b). There

were no obvious changes in the right side of 200-90m coal pillars. The horizontal displacements from 90m to the working face position increased linearly. After the displacements reached 70mm, the horizontal displacements of each point increased rapidly. At -90m, the horizontal displacements reached 500mm. The horizontal displacements of the upper part of the coal pillar changed faster compared with those of the #6, #7 and #8 monitoring points. The two sides of the coal pillars have undergone three changes including "steadily increasing and rapidly increasing" and the maximum displacement value was reached at 90-100m of the goaf. Under one-sided mining, the horizontal displacements of coal pillars are about 35mm, which are relatively stable.

From the aforementioned, it can be observed that 35m coal pillar was affected by "single and goaf-side" mining, so the roadway roof plates and the two sides of coal pillars have undergone three changed displacement characteristics and completely collapsed in the goaf. 35m coal pillar can effectively prevent the occurrence of dynamic disasters in deep mines and play a supporting role.

7. Conclusion

(1) Under static loads, the rules of disturbance stress distributions, displacements, and plastic failures of coal pillar are symmetrical, and the rules for the left and right sides are basically similar, which will not cause dynamic disasters on the two roadways. After both sides of coal pillars were mined in turn, plastic damage ranges expanded with decreases in coal pillars. The displacement characteristics of coal pillars were changed from "pry plate type" to "sector" failure, and stable "trapezoidal" structures appeared inside the 40m and 35m coal pillars. The stress evolves from "concave" distribution to "V" distribution between peaks, and the stress peak value on the side of the 416 working face is the largest and should be concentrated from the middle of the coal pillar to the bottom.

(2) The "trapezoidal" plastic failures formed inside the 35m coal pillars coincided with the "trapezoidal" movement characteristics. In case the coal pillar is less than 28m, its internal plasticity is completely destroyed, and dynamic instability easily occurs at the junctions of the two sides of the coal pillars and roofs. Finally, it is determined that coal pillar sizes of the working face with overlength at deep and large mining heights should be 35m.

(3) Through field measurement, under the influence of "one-sided mining along the goaf", 35m coal pillar has undergone three kinds of different displacement characteristics at the roadway roof plates and the two sides of coal pillars and completely caved in the goaf. 35m coal pillars have played a good supporting role and can restrain the occurrence of dynamic disasters.

Declarations

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Cui Feng contributed to the conception of the study and revised the manuscript.

Lei Zhaoyuan has contributed to the design of the work and have drafted and revised the manuscript.

Liu Jianwei has made the contribution to the acquisition and analysis.

Lai Xinging has made the contribution to the interpretation of data.

Yi Ruiqiang has conducted the experiments in the work.

All the authors have approved the submitted version. All the authors have agreed both to be personally accountable for their own contributions and to ensure that questions related to the accuracy or integrity of any part of the work are appropriately investigated, resolved, and the resolution documented in the literature.

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Figures

Figure 1

Mine location and stratum condition. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Working face position

Figure 3

Distribution characteristics of overburden caving and disturbance stresses

(a) Flooring heaving

(b) Undercutting height

(c) Foot heaving

(d) cracking

Figure 4

Emerging phenomena of mine pressure on both sides of coal pillar

Figure 5

Establishment of numerical simulation

Figure 6

Plastic failure characteristics of coal pillars

Figure 7

Stress distribution characteristics of Coal pillars under static load

Figure 8

Vertical displacement characteristics of each coal pillar

Figure 9

Vertical displacement characteristics of each coal pillar

Figure 10

Plastic distribution characteristics of coal pillars for stopping on 416 working face

Figure 11

Plastic distribution characteristics of 418 mining coal pillars

Figure 12

Stress distribution characteristics under unilateral mining

Figure 13

Stress variation characteristics of coal pillars

Figure 14

Stress distribution characteristics of coal pillars in goaf-side stoping

Figure 15

Variation characteristics of stress peaks

Figure 16

Motion characteristics of coal pillars for stopping at 416 working face

Figure 17

Horizontal displacement characteristics of six kinds of coal pillars

Figure 18

Motion Characteristics of Coal Pillars for Stopping at the 416-Working Face

Figure 19

Horizontal Displacement Characteristics of Coal Pillars

Figure 20

Support Construction on Both Sides of Coal Pillar

Figure 21

Monitoring scheme

Figure 22

Settlement characteristics of roofs on both sides of 35m coal pillars

(a) Displacements of mining two sides of 416

(b) Displacement of mining two sides of 418

Figure 23

Displacement characteristics of two sides of 35m coal pillars