INTRODUCTION

In order to improve the coefficient of coal mining, China coal mines usually adopt the longwall mining method and roadway driving along next goaf. The coal pillar is located between the goaf and next longwall mining face. When choosing the width of the coal pillar, the section of the tunnel after the coal pillar's deformation must meet the demand for pedestrian and material transporting and ventilating. In recent years, the depth of coal mining has been increasing at an annual rate of 6-10 m, and the deformation of the coal pillar has increased, so it is necessary to fully understand the deformation law of coal pillar and to provide a reliable basis for the retention of coal pillar width and the design of roadway support scheme. Many scholars have done some research on the influential factor of coal pillar deformation. The interfacial stress and the width of limit equilibrium area are affected by mining depth, interfacial friction angle, cohesive force, coal seam thickness, lateral supporting resistance, and stress concentration coefficient.1-4 Based on the coal mechanics, equilibrium equation of the limit equilibrium theory, the relationship between the inner stress and the width of the plastic area at the edge of the coal pillar,
and the calculation formula of coal pillar width are obtained. The deformation of the coal pillar mainly includes collaborative deflection compression deformation induced by the concentration load and the gravity settlement deformation caused by the concentration load. The rational longwall pillar width was set as 8 m, and the field monitoring results confirmed the feasibility of this pillar size. In deep mining, the energy accumulation and release cause a discontinuous damage in the heterogeneous coal mass, and the lateral deformation of coal pillar shows discontinuity, step, and mutation characters. There are different views on the reserved coal pillar width. The results indicate that 5-m-wide coal pillars can ensure that the chain pillars are at a lower stress level and the deformation of roadway surrounding rock is in a more reasonable range. Industrial experiments show that when the chain pillar width is 5 m, the deformation of roadway surrounding rock can meet the requirements of working face safe production. The numerical results agreed well with field measurement and observations, and the industrial experiment results further validated the results of the numerical simulation. A method is proposed for setting a reasonable width of coal pillars, and the specific width of coal pillars is designed and applied in engineering practices based on the above research. The influence range of lateral support pressure in the goaf is 50-60 m, the width of low-stress area is 12-15 m, and after considering various factors such as goaf and bolt support, the width of coal pillar was finally determined to be 5 m. In addition, results of this paper also have important theoretical significance and valuable reference for surrounding rock control technology of gob-side entry driving with narrow coal pillar under special geological condition. Large coal pillars of the working face with large mining height will lead to low recovery rate, so the width of coal pillar was determined to be 8 m. According to the characteristics of coal pillar in working face with steep coal seam, the reasonable size of coal pillar was obtained to ensure the stability roof section of goaf. The ratio of width to height of narrow coal pillar in gob-side entry driving has the greatest influence on surrounding rock deformation. In the evolution process of supporting pressure in each stage after the formation of coal pillar, there is stable elastic core area in the 20-meter-wide coal pillar, which can be optimized to improve the recovery rate. Some deformation space can be reserved in deep high-stress roadway tunneling, which can realize the transformation of surrounding rock from nonuniform and non-coordinated deformation to uniform and coordinated deformation to some extent. In the mining with filling of coal mine, the mechanics action of the coordination support systems with backfilling, coal pillar, and roof load-bearing rock stratum can control the surface subsidence to the minimum value. With the in-depth study of coal pillar deformation characteristics, the strength of roadway backfill should be in dynamic coordination with roof pressure. The failure of coal and rock mass in semi-coal-rock roadway showed inhomogeneous deformation, and the overall support technology which is mainly composed of roof prestressed long cable and high-rigidity truss cable has a good effect on this kind of roadway. The maximum principal stress of coal pillar increases with the expansion of distance between structural planes and the dip angle of structural planes, and the deformation of coal pillar decreases with the increase in the distance between structural planes. In the process of secondary excavation, the coal pillar is always under high stress. In the horizontal rock strata, there is a neutral surface area in the small coal pillar without deformation or small deformation under the condition of gob-side entry driving. Statistics show that about 55% of China’s recoverable coal reserves exist in inclined strata. Especially, with the decreasing of shallow coal resources, it is necessary to further study the deformation characteristics and deformation mechanism of coal pillars in deep inclined strata. At present, most of the research focused on the deformation and stress analysis of coal pillars in the roadway of horizontal rock strata, but lacks the research on the deformation, plastic area expansion, and stress distribution of coal pillar in inclined strata roadway.

2 | BACKGROUND

The Xieqiao Coal Mine Corporation is located in Anhui province, China. It is located in the east of China and can produce more than 8 million ton coal per year. We selected three roadways of this coal mine corporation. They are located in the different coal seams of this mine. Before we confirmed the supporting parameter, the type and the feature of surrounding rock have been tested in laboratory. The geological parameter of different roadways is shown in Table 1.

As shown in Figure 1, different roadways have the same section of inclined top echelon and the waist is perpendicular to the base. Support parameters such as bolt and cable are shown in Table 2. The multipoint displacement meter and borehole stress meter were used to monitor the deformation and vertical stress change of coal pillar. The coal pillar, surrounding rock parameters of roadway, and the layout of monitoring equipment are shown in Figures 2 and 3. Figure 4 shows the equipment for monitoring the displacement of internal point.

3 | DATA ANALYSIS ABOUT COAL PILLAR DEFORMATION

3.1 | Analysis of coal pillar surface deformation

With the decrease in distance between working face and the monitoring situation, small coal pillar deformed because of
the surrounding stress improved. As shown in Figure 5, the section of roadway becomes smaller and the surface of coal pillar moves toward the center of the roadway. Based on the data of monitoring, we got the curve of coal pillar surface deformation as shown in Figure 6 and the curve of coal pillar surface deformation velocity as shown in Figure 7.

It can be found from Figure 6:

There is a nonlinear relationship between the distance from the monitoring points to the working face and the deformation of the coal pillar surface. The farther the distance between the monitoring point and coal pillar surface, the smaller the deformation. Instead, the closer the distance is, the larger the deformation on the coal pillar surface is.

When the distance between the monitoring points to the working surface is over 100 m, the deformation of coal pillar surface in different roadways increase sharply, and the final deformation is close to each other, which is less than 10% different from the average value as shown in Table 3.

It can be found from Figure 7:

When the distance between the monitoring point to the working surface is over 100 m, the deformation velocity of coal pillar surface is slow, and the deformation velocity increases rapidly when it is less than 100 m.

The peak of deformation velocity appeared at the distance of 10 m from the monitoring point to the working face. This is because the working face is close to monitoring points, monitoring points are severely affected by the front pressure of the working face, and the deformation velocity peaked at about 10 m from working face. As the working face continues to advance, when the distance is <10 m, the monitoring point may be unable to measure due to the influence of mining activities, or it has been damaged and cannot record the displacement value.

|                               | 13 318 roadway   | 11 613 roadway   | 12 521 roadway   |
|-------------------------------|------------------|------------------|------------------|
| Ground elevation (m)          | +20.8~+27.6      | +21.3~+26.9      | +22.3~+24.9      |
| Working face elevation (m)    | −620~−511        | −608~−723        | −642~−720        |
| Coal seam                     | 8#               | 13-1#            | 11-2#            |
| Coal average thickness (m)    | 2.75             | 5.53             | 2.4              |
| The dip of coal seam          | 189°~210°        | 185°~200°        | 180~200°         |
| Dip angle of coal seam        | 10°~15°, average 12.5° | 10°~15°, average 12° | 10°~18°, average 14.5° |
| Upper roof                    | Quartzose sandstone, about 21.75 m thick, off-white, medium-fine grained, fracture development, rigidity | Medium sandstone, about 5.47 m thick, siliceous cementation, slow-wave bedding, local facies change to sandy mudstone | Fine Sandstone, about 9.75 m thick, light gray-light gray, slow-wave bedding, a small crack |
| Immediate roof                | Sandy mudstone, about 1.9 m thick, with a high ratio of sand | Mudstone and coal, about 4.5 m thick, deep gray, contain a few plant fossil fragmentation, fragile | Mudstone, about 2.9 m thick, gray-dark gray, fracture slip surface development, plant fossil fragmentation |
| Immediate floor               | Mudstone, about 1.44 m thick, gray-dark gray, the upper part is mainly clay, horizontal bedding included, fragile | Mudstone, about 2.65 m, dark gray, block structure, contain plant rhizome fossils | Mudstone, about 4.2 m thick, dark gray, thin silty layer with rare plant fossil fragmentation |

**Table 1**: Roadways of 13 318, 11 613, and 12 521 surrounding rock geological parameter.
3.2 Analysis of absolute displacement of monitoring point in coal pillar

The multipoint displacement meter is used to monitor the displacement of monitoring points in different depths of coal pillar toward the center of roadway, and each displacement meter has six monitoring points as shown in Figure 3. In Figure 8, the numbers in the upper right corner represent the different distances between the interior of the coal pillar and the surface. Figure 8 shows the monitoring result of coal pillar.
pillars in different roadways, the following conclusion can be drawn:

Monitoring points of different depths in the coal pillar all move toward the center of the roadway, and there is no central plane without displacement in the coal pillar.

The farther the distance from the coal pillar surface is, the smaller the absolute displacement of the monitoring point to the center of the roadway is.

### 3.3 Analysis of interval length of monitoring point inside coal pillar

Figure 9 shows the change in the distance between adjacent monitoring points in different roadways. The observation results revealed the following two findings:

1. When the distance between the monitoring point and the working face is more than 100 m, the monitoring points near the coal pillar surface start to move relatively. When the distance between the monitoring point and the working face is less than 100 m, the internal monitoring point whose distance from the coal pillar surface is more than 3 m starts to move relatively, which indicates that the deformation and breakage of the coal pillar gradually extend from the surface to the interior.

2. The relative displacement between adjacent monitoring points does not always increase, but also decreases, which indicates that there is a phenomenon of crack closure in the deformation process during macrocrack occurs in the coal pillar.

### 3.4 Measurement and analyses of borehole stress in coal pillar

Borehole stress meter is a model ZLGH-40 as shown in Figure 10. The diameter is 40 mm, and two groups (6 monitoring points for each group) are assigned in the same section of roadway. Vertical and horizontal layout for meters are shown in Figure 3, and these meters are located inner 1 m, 2 m, 3 m, 4 m, 5 m, and 6 m, respectively. Numbers 1, 3, 5, 7,
9, and 11 are designed for horizontal stress, and numbers 2, 4, 6, 8, 10, and 12 are designed for vertical stress. Borehole stress meter is located in 1.2 m from floor. The interval space is about 0.8 m between different points. As for stress distribution in one section of the roadway, an approach of adopting transformation of different distance for the same points is employed to calculate the stress distribution in the same section with 6 monitoring points under different distance such as 10 m, 20 m, and 60 m, which are shown in Figure 11 for vertical stress and Figure 12 for horizontal stress.

Figure 11 demonstrates that with the decrease in distance with working face, vertical stress goes up for every borehole and the bigger the borehole point depth is, the bigger the increasing value of stress is. Specifically, the increasing volume of vertical stress for 0‐2 m area is slight as shown in Figure 11 while 2‐4 m area shows obvious rise for stress. Further, the biggest increasing stress is 4‐6 m area of pillar with approximately 18 MPa. The results indicate that increasing vertical stress experiences the most significant increase for core zone of pillar which does not show a rugby-shaped distribution. Compared with conclusions of fractures propagation, it is consistent for both two investigations. Under leading abutment pressure, deformations of coal‐rock and fracture propagation appear in the pillar toward roadway center which provide partial space for energy release of surrounding rock. This mechanism gives rise to the increasing vertical stress of different depths of borehole.

As shown in Figure 12, there is a different tendency for increasing horizontal stress with that of vertical stress. Basically, the entire curves show that horizontal stress for every monitoring borehole increases within 0-4 m area of pillar and reaches the peak value at 4 m point. As for 4-5 m area of pillar, there is a decrease while 5-6 m area shows a sharp increase in borehole 6 with the greatest increasing stress volume. Ultimately, three‐dimensional distribution for vertical stress and horizontal stress is shown in Figures 13 and 14 by applying interpolation algorithm. Under different distance, stress distribution has different characteristics such as increasing speed and absolute volume. Besides, there are distinct characteristics between vertical stress distribution and horizontal stress distribution.

4 | NUMERICAL MODEL ESTABLISHMENT

4.1 | FLAC3D deformable block and contact model and microparameters

The discontinuity of rock materials (such as joints, cracks, bedding, and different mineral compositions) causes continuum mechanics to exhibit significant deficits. Compared with the finite element method (FEM), the discrete element method (DEM) can not only represent the broken states and the strong nonlinear mechanical phenomena of surrounding rocks in deep roadway but also better reveal the failure process of the roadway by simulating the fracture, movement, and large deformation. The computational domain in FLAC3D is discretized into blocks by using a finite number of intersecting discontinuities (Itasca, 2014). The discontinuities are treated as boundary conditions between blocks. Large displacements caused by the body motion of individual blocks, including block rotation, fracture opening,
and complete detachments, are straightforward in FLAC3D. Most conventional studies have adopted several sets of joints with a regular distribution to represent the breaking state of surrounding rock, but it is difficult to simulate the real structural features and dynamic mechanical behavior of surrounding rock.
In this numerical model, a rock mass is represented as assemblages of trigon blocks connected by contacts between them; individual blocks behave as either rigid or deformable material.\textsuperscript{25-28} The motion of a block is described by Newton’s second law of motion under disturbance forces from applied loads, body forces, and forces from adjacent blocks.

Because the tensile strength of rocks is much smaller than its compressive strength, the Mohr-Coulomb elastoplastic constitutive model is selected to realize the tension failure of the block (Itasca, 2008). The Coulomb friction law is applied at the contacts, which can realize the sliding or opening of the contact, and it is very suitable to simulate the failure process of rock roadway after excavation. The contact behavior of contact was simulated by a spring rider, and the force was divided into normal stress and shear stress. The cohesion ($C_b$), friction angle ($\phi_b$), and tensile strength ($\sigma_{tb}$) of blocks were based on the previous study (Yang et al., 2014) with the bulk modulus ($K$) and shear modulus ($G$) of the blocks in the numerical model listed in Table 4.

### 4.2 Numerical model and simulation schemes of the 12 521 roadway

A numerical model of the 12 521 roadway was created by using FLAC3D. Figure 15 shows the geometry of the model, which is based on the lithology of the 12 521 roadway illustrated in Table 4 and Figure 16. The numerical model has dimensions of 40 m (width) and 40 m (height). The main aim of this study is to investigate the behavior of the coal pillar in the surrounding rock of the roadway caused by the different distance of the working face. Small
zone with average length less than 0.3 m was generated in the coal pillar and the area of interest to increase the computational efficiency; and small zone with average length less than 0.3 m was generated in the surrounding rock of the tunnel; the remainder of the model was zoned with average length less than 0.5 m that could better simulate the strata and get better simulation. Vertical stress was applied to the upper boundary to simulate the overburden stress. The horizontal displacement was constrained along the lateral boundaries of the model, and the vertical and horizontal displacements were fixed at the bottom boundary. The model was run to equilibrium to generate the in situ stress before the road was excavated by deleting the block to simulate the deformation with the effected of the working face.

In this section, firstly, the influence of coal pillar on the goaf formed by mining on the previous working face was simulated. Then, the roadway of working face was excavated and bolt support was applied. After the roadway was stabilized, the model stopped calculating. Finally, the boundary stress of the model was added to simulate the influence of working face front pressure, and the model is calculated until the roadway is stable.

5 | SIMULATED RESULTS OF COAL PILLAR

Combined with the actual mining procedure of working face, the simulation process of previous mining face was simplified. In order to ensure the safety of coal resources mining, the last working face roadway was generally backfilled in the actual coal mining process. Therefore, the excavation of previous working face roadway was not considered in the modeling process.

5.1 | Validation of numerical simulation results

In order to verify the reliability of the numerical simulation results consisting of the industrial experiments, the validations of the numerical simulation results by comparing the outputs of the model with field observations and other investigations are needed. Figure 17 shows the comparison between the measured and simulated convergences of the
monitoring point 1 m away from the coal pillar surface during the working face mining. Both the measured and simulated displacement curves indicate a similar change trend. Therefore, the numerical simulation of coal pillar deformation matches industrial experiments very well.

5.2 | The plastic zone of coal pillar

When deep rock is excavated, local stress concentration will appear in the surrounding rock. The coal pillar is affected by the multiple mining effect of the roadway excavation of the last working face, the roadway excavation of this working face, and the front pressure of this common working face. The pressure that coal pillar bears far exceeds the ultimate strength of coal pillar, make coal pillar produces deformation the yield area that cannot restore, it is coal pillar plastic zone namely.

As shown in Figure 18, the shallow surrounding rock within 2.5 m of the roof and 6 m of the floor of the working face enters plastic state after being affected by the mining of previous working face, and part of area within 3 m of the coal pillar also enters plastic state.

As shown in Figure 19, when the roadway of working face is excavated, the plastic zone of previous working face and surrounding rock of roadway extends to the coal pillar simultaneously. The coal pillar and roadway within 2.5 m of the roof and 4 m of the floor enter plastic state, and the plastic zone is concentrated in the upper right and lower right of coal pillar, respectively.

As shown in Figure 20, under the influence of the front pressure of the working face, the plastic zone extends about 1 m to the middle area of coal pillar.

5.3 | The Coal pillar stress

Figure 21 shows the distribution of vertical stress of coal pillar after the roadway is excavated. There is a tensile stress concentration area on the surface of coal pillar, the maximum tensile stress value is 0.7 MPa, and its tensile stress value decreases to 0 at a distance of 0.5 m from the surface of the coal pillar. Outside this range, the vertical stress value in the coal pillar increases gradually, reaching the original rock stress (13.5 MPa) 2.5 m away from the surface of the coal pillar, and the compressive stress concentration phenomenon appears in the area around 6 m away from the surface of the coal pillar. The maximum
Compressive stress value reaches 40 MPa, which is about triple of the original rock vertical stress. Figure 22 shows the vertical stress change of coal pillar under the influence of the front pressure of the working face. Compared with the previous stage, the maximum vertical stress area in the coal pillar moves about 1 m toward the goaf and reaches the maximum vertical stress value of 38.6 MPa at a distance of 7 m from the surface, which is 1.4 MPa lower than the previous stage.

As shown in Figure 23, horizontal stress relief appears on the surface of the coal pillar after the roadway is excavated, and the horizontal stress value of the coal pillar gradually decreases to 0. After that, the horizontal stress value of the original rock at 4 m away from the coal pillar surface reaches 13.5 MPa. Outside the range of 4 m, the horizontal stress value gradually increases, and the maximum horizontal value reaches 28 MPa. As shown in Figure 24, under the effect of the front pressure of working face, the area of stress relief on the surface of the coal pillar expands slightly. The range of 4-5 m within the coal pillar from the surface reaches the original rock horizontal stress value (13.5 MPa). Outside the range of 5 m, the horizontal stress value gradually increases, and the maximum value reaches 30 MPa, which increases by 2 MPa compared with the previous stage.
Figure 25 shows the vertical stress change of each monitoring point after being affected by the front pressure of the working face. Within 4 m from the surface of the coal pillar, the vertical stress increment of the coal pillar is large, and the change rate of vertical stress is about 8.34 MPa/m. After that, the vertical stress increment gradually decreases, and the change velocity is about 2.35 MPa/m. Compared with this stage in the previous stage, the maximum vertical stress values at the monitoring points 5 m and 6 m decrease by 1 MPa and 1.5 MPa, respectively.

Figure 26 shows the horizontal stress change of each monitoring point after being affected by the front pressure of the working face. Within 4 m from the surface of the coal pillar, the horizontal stress increment of the coal pillar is large, and the change rate of vertical stress is about 2.89 MPa/m. After that, the vertical stress increment gradually decreases, and the change velocity is about 2.33 MPa/m. Compared with this stage in the previous stage, the maximum horizontal stress values at the monitoring points 5 m and 6 m increase by 1.7 MPa and 2 MPa, respectively.

Table 4 Numerical model of rock mechanics parameters

| Stratum          | Bulk modulus (Gpa) | Shear modulus (Gpa) | Friction angle (º) | Cohesion (Mpa) | Tensile strength (Mpa) | Density (kg·m³) |
|------------------|--------------------|---------------------|--------------------|----------------|------------------------|-----------------|
| Overlying rock   | 11.10              | 10.8                | 35                 | 12.85          | 9.2                    | 2500            |
| Mudstone         | 10.96              | 10.5                | 32                 | 11.18          | 5.56                   | 2400            |
| Fine Sandstone   | 10.86              | 10.3                | 34                 | 11.5           | 6.66                   | 2600            |
| Sandstone        | 10.86              | 8.26                | 30                 | 11.80          | 4.20                   | 2600            |
| Mudstone         | 0.6                | 0.45                | 30                 | 0.8            | 0.5                    | 1800            |
| Coal             | 2.4                | 6.7                 | 28                 | 3.00           | 0.76                   | 1700            |
| Mudstone         | 0.6                | 0.45                | 30                 | 0.8            | 0.8                    | 1800            |
| Fine Sandstone   | 10.86              | 9.26                | 30                 | 11.8           | 5.2                    | 2600            |
| Mudstone         | 10.25              | 7.54                | 28                 | 11.2           | 2.06                   | 2450            |
| Sandstone        | 9.49               | 8.26                | 30                 | 12.44          | 2.66                   | 2500            |

5.4 The coal pillar displacement

As shown in Figure 27, after the roadway of working face is excavated, the deformation range within the coal pillar reaches 4 m, and the deformation within 3 m is obvious. The maximum deformation of the surface of the coal pillar toward the roadway center is 690 mm. As shown in Figure 28, under the influence of the front pressure of working face, the deformation range of coal pillar reaches 6 m, and the maximum...
The deformation amount and range of coal pillar are further increased. As shown in Figure 29, after the roadway of working face is excavated, the displacement variation of monitoring points within and outside the 3 m range of coal pillar surface is 213.5 mm and 83.6 mm, respectively. Under the influence of the front pressure of working face, the displacement variation of monitoring points within and outside the 3 m range of coal pillar surface is 223 mm and 123.3 mm, respectively, and the displacement increment of monitoring points 1, 2, and 3 is larger than that of monitoring points 4, 5, and 6 in the two stages.

6 | DISCUSSION

6.1 | Analysis of coal pillar displacement

Affected by the mining of last working face and the tunneling of the roadway of working face, the plastic zone inside the coal pillar expands stably. The coal pillar, the roof, and floor of the roadway and the surrounding rock of the low side of the roadway all enter the plastic state, and the maximum vertical stress in the coal pillar is 40 MPa, which is about triple of the original rock vertical stress. This is because the superposition of mining stress and original rock stress caused by multiple mining influences, which exceeds the compressive strength of coal and rock mass inside the coal pillar, resulting in the deformation of coal pillar surface toward the roadway center, and the maximum surface displacement reaches 690 mm.
**Figure 19** Plastic zone distribution of coal pillar in roadway excavation

**Figure 20** Plastic zone distribution of coal pillar in working face mining

**Figure 21** Vertical stress distribution of coal pillar in roadway excavation
**FIGURE 22** Vertical stress distribution of coal pillar in working face mining

**FIGURE 23** Horizontal stress distribution of coal pillar in roadway excavation

**FIGURE 24** Horizontal stress distribution of coal pillar in working face mining
From Figures 8D and 29, the displacement of monitoring point within 3 m of coal pillar surface is smaller than that outside 3 m, and the further it is from the coal pillar surface, the smaller the displacement of the monitoring point will be. The monitoring data are consistent with the simulation results. It shows that under the effect of 2.5 m bolt, the influence range of roadway surface displacement is mainly concentrated within 3 m, and there is no zero displacement point within the monitoring range.

6.2 | Analysis of coal pillar stress

The coal pillar enters plastic state after being affected by multiple mining influences. Meanwhile, the surface of the coal pillar moves 1460 mm toward the center of the roadway. Under the influence of working face front pressure, the large deformation of the coal pillar releases the deformation potential energy accumulated in the process of stress concentration, resulting in a larger zone of coal pillar stress relief. The maximum value of vertical stress in the coal pillar decreases compared with the previous stage. The shape of the vertical stress concentration area changes from oval to rectangle, and the vertical stress peak area moves 1 m to the goaf side.

Under the influence of the front pressure of working face, the horizontal stress value within the range of 2.5-3 m from the coal pillar surface is smaller than the previous stage. Outside this range, the horizontal stress difference between the second stage and the first stage gradually increases. This is because the tail of the bolt is affected by the tension caused by the surface deformation of the coal pillar, resulting in the decrease in the horizontal stress value of the coal pillar near the end of the bolt. The simulation results are consistent with the trend of horizontal stress monitoring.

7 | CONCLUSION

In the study, the deformation, stress, and plastic zone of coal pillar are analyzed by field observation and numerical simulation. The following conclusions can be drawn:

![Vertical stress curve inside the coal pillar](image1)

**FIGURE 25** Vertical stress curve inside the coal pillar

![Horizontal stress curve inside the coal pillar](image2)

**FIGURE 26** Horizontal stress curve inside the coal pillar

![Horizontal displacement distribution of coal pillar in roadway excavation](image3)

**FIGURE 27** Horizontal displacement distribution of coal pillar in roadway excavation
1. After being affected by multiple mining influence, the large deformation of coal pillar mainly occurs within the range of 3 m from the surface, the impact on the interior of coal pillar beyond the range of 3 m is relatively small, and there is no zero displacement surface within the monitoring range of 6 m.
2. After the working face is excavated, the vertical stress peak area appears at the position 6 m away from the coal pillar surface. The influence of the front pressure of the working face changes the shape of the vertical stress peak area and makes the vertical stress peak area expand, causing the vertical stress concentration area in the coal pillar to move 1 m toward the goaf side.
3. Numerical calculation and field test show that under the influence of the front pressure of the working face, the surface deformation of coal pillar will cause a certain extent of stress release, and the vertical stress value in the coal pillar will not increase sharply. Under the influence of reasonable supporting structure, the postpeak strength of coal pillar can maintain the roadway surrounding rock deformation within the controllable range and guarantee the secure use of roadway during service.

ACKNOWLEDGMENT

Financial support for this work, provided by the National Natural Science Foundation of China (No. 51774133, No. 51434006, No. 51804111) and the Hunan Provincial Natural Science Foundation of China (No. 2017JJ2088), is gratefully acknowledged.

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**How to cite this article:** Wu H, Wang X, Wang W, Peng G, Zhang Z. Deformation characteristics and mechanism of deep subsize coal pillar of the tilted stratum. *Energy Sci Eng*. 2020;8:544–561. https://doi.org/10.1002/ese3.546