Numerical investigation of failure evolution for the surrounding rock of a super-large section chamber group in a deep coal mine

Yunliang Tan¹ | Deyuan Fan¹ | Xuesheng Liu¹,² | Shilin Song¹ | Xianfeng Li³ | Honglei Wang¹

¹State Key Laboratory of Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao, China
²State Key Laboratory of Water Resource Protection and Utilization in Coal Mining, China Energy Group Co., Ltd., Beijing, China
³Shandong Energy Group Co. Ltd., Jinan, China

Correspondence
Xuesheng Liu, State Key Laboratory of Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China. Email: xuesheng1134@163.com

Abstract
The stability control of surrounding rock for a large or super-large section chamber group is a difficult technical problem in deep mining conditions, and this stability control has become one of the most important factors restricting the safety of a large-scale coal mine. Based on the in-site geological conditions of a super-large section chamber group that functions for a coal gangues separation system in the Longgu Coal Mine, we first researched the stress, deformation, and failure characteristics of the in-site chamber group surrounding rocks by using the FLAC3D software. Simulation results showed that the maximum vertical stress, deformation, and failure range of the surrounding rock for a super-large section chamber group are larger than those of an ordinary section chamber. In addition, the roof subsidence and the plastic zone radius at the intersection are obviously larger than that of other parts, which increase by approximately 50.8% and 44.4%, respectively. Therefore, the chamber group intersection should be taken as the key area for surrounding rock control. Then, the influences of two key parameters of the chamber group, spacing and angle, were researched in detail to help in the design of the chamber group. Results show that when the chamber spacing is 80 m, the interaction begins to occur. When the angle is 70°, the stress of the surrounding rock and roof subsidence reach the minimum. Thus, the optimum chamber group parameters are determined to be a spacing of 80 m and an angle of 70°. Finally, from the perspective of chamber group stability, the optimal chamber group parameters can better meet the normal use for the super-large section chamber group. This research provides a reference for the design of a super-large section chamber group under the same or similar conditions and provides a strategy for controlling the surrounding rock.

Keywords
chamber angle, chamber group, chamber spacing, deep coal mine, failure evolution, super-large section
1 | INTRODUCTION

Coal resources account for 70% and 60% of the primary energy production and consumption structure, respectively, and they have always been the main energy source of China. In recent years, the mining scale and intensity of coal mines have gradually increased with the prosperity of coal production each year, and many large and super-large section chambers and chamber groups have emerged. The cluster distribution of super-large section chambers makes the interaction between the chambers fierce, and it is very easy to cause dynamic accidents such as roof fall and rib spalling. This interaction has become a major technical problem restricting the safe mining for coal mines. Currently, some scholars have performed research on the failure evolution and control methods for the surrounding rock of chamber group and have revealed the deformation and failure characteristics of the surrounding rock under various conditions. Unlike the single chamber, the deformation and failure evolution of chamber group are affected by many factors, including internal and external factor. In terms of internal factor, Qi et al studied two different chamber layouts by using FLAC3D and obtained a stable chamber group structure. He et al revealed the influence of excavation sequence on surrounding rock stability of soft rock intersection chamber group. For the external factor, Lin et al explored the causes of deformation and control measures for the large section chamber in complex geological structural area by analyzing numerical simulation and field measurement results. Cheng et al revealed the rock displacement law considering the lithological characteristics in the process of chamber group excavation. Sun et al revealed that dynamic load disturbance makes the stability of surrounding rock of chamber group decline sharply and intensifies the stress concentration. Under the combined action of superimposed stress generated by the excavation and external factors, chamber groups interact with each other, causing local destruction and even chain instability in the whole chamber group.

However, the shallow coal resources have gradually become exhausted with the long-term continuous high-intensity mining of Chinese coal resources, and coal mining is gradually transferring to the depths. In deep mining conditions, the mechanical properties and engineering response of coal rock have changed under the combined influence of high geostress and strong dynamic disturbance, the surrounding rock deformed and fractured more seriously which makes it more difficult to control. Li et al used numerical simulation and field measurement to analyze the instability mechanism of the surrounding rock in a soft rock roadway under high-stress conditions and proposed the surrounding rock stability control method. Qian et al determined the influence of creep and time-dependent behavior on the stability of deep underground chamber through large fault zones in argillaceous rocks by in-site monitoring. Wang et al deduced the critical load of initial buckling and continuous buckling failure of a thick and hard floor by using thin plate theory and revealed the floor failure mechanism of a deep large chamber. Sun et al studied the mining-induced impacts on the stability, proposed a control strategy of overlying multi-tunnels with backfill mining by using a numerical simulation method, revealed that the panel width and advancing distance have an important influence on overlying multi-tunnel stability in a deep coal mine.

The above research studies have determined the deformation and failure characteristics of chamber group surrounding rock under some specific geological and mining conditions, which provided some support for stability control. However, there are a few studies on the deformation and failure evolution of the surrounding rock for a deep super-large section chamber group. In addition, the key parameters affecting its chain instability have not been thoroughly studied. Therefore, this paper takes coal gangue separation system of Longgu Coal Mine as the research background. FLAC3D numerical simulation software is used to reveal the failure evolution and characteristics of the surrounding rock for a deep super-large section chamber group. On this basis, different chamber group spacings and angles were simulated separately, and the optimal spacing and angle were determined through comparative analysis of the simulation results.

2 | ENGINEERING OVERVIEW

Longgu Coal Mine, situated in the middle south region of Juye Coalfield, Heze City, Shandong Province, China, is approximately 20 km east of Juye County and 40 km west
| Column | No. | Lithology     | Thickness/m | Petrographic description                                      |
|-------|-----|---------------|-------------|--------------------------------------------------------------|
| 1     | Siltstone | 12.4 ~ 20.2   | Dark gray, horizontal bedding development, uneven fracture |
| 2     | Mudstone | 5.3 ~ 11.1    | Grey green, argillaceous and layer structure, ripple bedding fracture |
| 3     | Fine sandstone | 2.5 ~ 6.3    | Dark gray, fine-grained round structure, intermittent wavy bedding development |
| 4     | Siltstone | 2.6 ~ 6.0    | Dark gray, vertical bedding development, uneven fracture |
| 5     | Fine sandstone | 3.8 ~ 4.4    | Dark gray, fine-grained round structure, intermittent wavy bedding development |
| 6     | Siltstone | 6.3 ~ 10.7    | Dark gray, vertical bedding development, uneven fracture |
| 7     | Mudstone | 5.6 ~ 9.0     | Grey green, argillaceous and layer structure, ripple bedding fracture |
| 8     | Fine sandstone | 4.2 ~ 6.2    | Dark gray, fine-grained round structure, intermittent wavy bedding development |
| 9     | Siltstone | 2.7 ~ 10.5    | Dark gray, vertical bedding development, uneven fracture |
| 10    | 3 coal | 3.2 ~ 6.8     | Black, strip and layer structure, dull luster |
| 11    | Siltstone | 3.6 ~ 6.2    | Dark gray, vertical bedding development, uneven fracture |
| 12    | Fine sandstone | 1.2 ~ 3.4    | Gray, muddy cementation, with small interlaced and gentle-wave bedding |
| 13    | Middle sandstone | 5.2 ~ 11.0   | Uniform bedding, muddy filling cracks, semi-hardness |
| 14    | Fine sandstone | 3.8 ~ 5.6    | Gray, muddy cementation, with small interlaced and gentle-wave bedding |
| 15    | Siltstone | 7.2 ~ 9.4     | Dark gray, vertical bedding development, uneven fracture |
| 16    | Mudstone | 9.6 ~ 14.8    | Grey green, argillaceous and layer structure, ripple bedding fracture |

**FIGURE 2** The stratigraphic sequence of coal seam and its roof and floor strata

**FIGURE 3** Layout and working process of the coal gangue separation system
of Heze City. The administrative division is subordinate to Longgu Town, Juye County. The location of Longgu Coal Mine is shown in Figure 1. The geological reserves of the Longgu Coal Mine are approximately 1.683 billion tons, the designed production capacity is approximately 6 million tons per year, and the designed service life is 82 years. Longgu Coal Mine has good development prospects.

The coal gangue separation system chamber group in Longgu Coal Mine mainly consists of four super-large section chambers: screening crushing chamber (SCC), screening product transferring chamber (SPTC), dense medium shallow groove separation chamber (DSSC) and slime water and medium chamber (SWMC). The coal gangue separation system chamber group is situated in the triangular area surrounded by the north main haulage roadway, No. 1 district rise and No. 1301 mining area. The mining area is situated in No. 3 coal, the buried depth is 778.6 ~ 848.6 m with an average of 813.6 m. The geological structure is simple which contains 0-3 layers of intercalated rocks, and the fissures are relatively developed. In addition, fat coal and coking coal are the main coal types in No. 3 coal of Longgu coal field, which are high-quality coal with low ash, sulfur, phosphorus, and high calorific value. The stratigraphic sequence of the coal seam and its roof and floor strata are shown in Figure 2.

The layout and working process of the coal gangue separation system are shown in Figure 3. The run-of-mine coal is transported from the north main haulage roadway to the SC chamber with a height of 9.0 m, width of 8.0 m, and length of 80 m. After screening and crushing operations, the raw coal is transported to the SPT chamber with a height of 9.0 m, width of 8.0 m, and length of 80 m. Moreover, the SPT chamber and the SC chamber are arranged vertically on the plane. Then, the raw coal is transported to the DSS chamber with a height of 9.0 m, width of 8.0 m, and length of 60 m. This chamber is perpendicular to the SPTC in plane and parallel to the SC chamber in the strike direction. Then, the clean coal is transported by belt conveyor to the north main haulage roadway, and the gangue is removed through the medium draining screen and discharged to the No. 1 district rise. To facilitate the addition of dense medium and the fluency of the scraping suction tank, the angle between the SWM chamber and the SC chamber is 74°, and the SWM chamber width is 8.0 m, height is 9.0 m, and length is 83 m.

3 | NUMERICAL SIMULATION METHOD AND SCHEMES

3.1 | Rock mass properties

The mechanical properties of the rock mass have an important influence on the stability of the surrounding rock, and different rocks have different mechanical properties. According to the suggested method of the International Society for Rock Mechanics and Rock Engineering (ISRM), the RLJW-2000 microcomputer-controlled rock servo test machine was used to carry out uniaxial compression tests on roof and floor rocks of the chamber group in the Longgu Coal Mine to obtain the mechanical parameters, as shown in Figure 4. The RLJW-2000 microcomputer-controlled rock servo test machine adopts a German DOLI full digital servo controller, with the advantages of high control accuracy, full protection function and strong reliability, which effectively ensures the reliability of the test results. In the test, the experimental materials used were 50 × 100 mm standard rock specimens, the axial load of the test machine was controlled by displacement loading, and the loading rate was 0.25 mm/min.

The uniaxial compression test results are shown in Table 1. The test results show that mudstone has an average uniaxial compressive strength of 37.25 MPa and Young’s modulus of 4.45 GPa. Coal has an average uniaxial compressive strength of 33.14 MPa and Young’s modulus of 4.26 GPa. Middle sandstone has an average uniaxial compressive strength of 64.11 MPa and Young’s modulus of 11.87 GPa. Fine sandstone has an average uniaxial compressive strength of 62.36 MPa and Young’s modulus of 10.21 GPa. Siltstone has an average uniaxial compressive strength of 57.52 MPa and Young’s modulus of 6.57 GPa.

However, the macroscopic strength of the rock mass is far less than the macroscopic strength of the rock samples due to the joints, cracks and different mineral compositions in engineering rock mass. Therefore, we use the strength reduction method to properly modify and adjust the mechanical parameters of the rock samples obtained in the experiment to adapt to the in-site geological conditions. The mechanical properties used in the numerical simulation model are shown in Table 2.

3.2 | Model development

According to the in-site geological conditions of the coal gangue separation chamber group in the Longgu Coal Mine, the FLAC3D numerical simulation software was adopted for establishing the numerical model, as shown in Figure 5. The simulation model size is 320 m × 320 m × 200 m, and the model is divided into 3 169 580 zones and has 3 270 141 grid points. The model has a fixed bottom boundary and a stress boundary at the top. The stress value is the self-weight of the upper rock strata, and the horizontal displacement constraint is applied to the rest of the model. In addition, Mohr-coulomb was selected as the constitutive model.

3.3 | Simulation schemes and procedures

3.3.1 | In-site chamber group

According to the in-site geological condition in the Longgu Coal Mine, the super-large section coal gangue separation
chamber group is simulated, as shown in Figure 6. The length of the SC chamber is 80 m. The length of the SPT chamber is 80 m, and the SPT chamber is perpendicular to the SC chamber. The length of the DSS chamber is 60 m, and the DSS chamber is perpendicular to the SPT chamber and parallel to the SC chamber. The length of the SWM chamber is 83 m, and the angle between the SWM chamber and the SC chamber is 74°. In addition, the height and width of each chamber in the coal gangue separation chamber group are 9 m × 8 m. Then, displacement monitoring points are arranged at the center of the rock-coal pillar surrounded by the chamber group to monitor the vertical displacement of the rock-coal pillar.

The detailed simulation process was as follows (Figure 7): (a) model generation; (b) determination of boundaries and rock properties; (c) monitoring point arrangement; (d) excavation of screening crushing chamber; (e) excavation of dense medium shallow groove separation chamber; (f) excavation of screening product transferring chamber; and (g) excavation of slime water and medium chamber.

### 3.3.2 Key parameters

#### Chamber group spacing

By changing the spacing between the SC chamber, the DSS chamber, the SPT chamber and the SWM chamber, 9 different simulation schemes of chamber group spacing were designed. The chamber group spacings were chosen as 100 m, 90 m, 80 m, 70 m, 60 m, 50 m, 40 m, 30 m, and 20 m. To control the research variables, the horizontal direction between chambers was set to be mutually perpendicular. At the same time, different simulation schemes of chamber group spacing were monitored, including the vertical displacement at the center of the rock-coal pillar.

| No. | Lithology      | Uniaxial compressive strength/MPa | Young’s modulus/GPa |
|-----|----------------|----------------------------------|---------------------|
| 1   | Mudstone       | 37.25                            | 4.45                |
| 2   | Coal           | 33.14                            | 4.26                |
| 3   | Middle sandstone | 64.11                           | 11.87               |
| 4   | Fine sandstone | 62.36                            | 10.21               |
| 5   | Siltstone      | 57.52                            | 6.57                |
TABLE 2  Mechanical properties used in the numerical simulation model

| Lithology     | Thickness (m) | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Friction (°) | Tensile strength (MPa) |
|---------------|---------------|-----------------|--------------------|---------------------|----------------|--------------|------------------------|
| Siltstone     | 16.3          | 2630            | 3.91               | 3.03                | 2.50           | 32           | 3.15                   |
| Mudstone      | 8.2           | 2210            | 2.56               | 1.72                | 1.55           | 26           | 1.58                   |
| Fine sandstone| 4.4           | 2540            | 7.82               | 5.69                | 9.00           | 22.5         | 4.15                   |
| Siltstone     | 4.0           | 2630            | 3.91               | 3.03                | 2.50           | 32           | 3.15                   |
| Fine sandstone| 4.1           | 2540            | 5.87               | 4.47                | 4.26           | 32           | 4.19                   |
| Siltstone     | 8.5           | 2630            | 2.74               | 1.87                | 3.00           | 25           | 2.70                   |
| Mudstone      | 7.3           | 2210            | 2.56               | 1.72                | 1.55           | 26           | 1.58                   |
| Fine sandstone| 5.2           | 2540            | 5.87               | 4.37                | 3.40           | 25           | 2.06                   |
| Siltstone     | 6.6           | 2630            | 3.91               | 3.03                | 2.50           | 32           | 3.15                   |
| Coal          | 5.0           | 1400            | 2.45               | 1.51                | 1.00           | 28.5         | 1.00                   |
| Siltstone     | 4.9           | 2630            | 2.74               | 1.87                | 3.00           | 25           | 2.70                   |
| Fine sandstone| 2.3           | 2540            | 5.87               | 4.47                | 4.26           | 32           | 4.19                   |
| Middle sandstone| 8.1       | 2580            | 6.82               | 3.69                | 8.00           | 24.5         | 5.15                   |
| Fine sandstone| 4.7           | 2540            | 5.87               | 4.47                | 4.26           | 32           | 4.19                   |
| Siltstone     | 8.4           | 2630            | 3.91               | 3.03                | 2.50           | 32           | 3.15                   |
| Mudstone      | 12.2          | 2210            | 2.56               | 1.72                | 1.55           | 26           | 1.58                   |

FIGURE 5  Numerical simulation model

FIGURE 6  In-site chamber group simulation scheme
surrounded by the chamber group and the vertical stress at the intersection of the chamber group. The simulation schemes of chamber group spacing and the measuring point arrangement are shown in Figure 8.

**Chamber group angle**

By changing the angle between the SC chamber and the SWM chamber in the horizontal direction, 8 different simulation schemes of chamber group angles were designed. The chamber group angles were chosen as 85°, 80°, 75°, 70°, 65°, 60°, 55°, and 50°. To control the variables, the distance between the SC chamber and the DSS chamber was set as 80 m, and the SPT chamber is perpendicular to the SC chamber and the DSS chamber. At the same time, displacement monitoring points are arranged at the center of the rock-coal pillar to monitor its vertical displacement, and stress monitoring points are arranged at the intersection of the chamber group to monitor the maximum vertical stress. The simulation schemes of the chamber group angle and the measuring point arrangement are shown in Figure 9.

**Simulation procedure**

The detailed simulation process was as follows (Figure 10): (a) model generation; (b) determination of boundaries and rock properties; (c) monitoring point arrangement; (d) fixed chamber group angle to simulate different chamber group spacings (100 m, 90 m, 80 m, 70 m, 60 m, 50 m, 40 m, 30 m and 20 m); (e) comparison of the results and determination of the optimal spacing; (f) using the optimal spacing to simulate various chamber group angles (85°, 80°, 75°, 70°, 65°, 60°, 55°, and 50°); and (g) compare the results and determine the optimal angle.

4 | RESULTS AND ANALYSIS

4.1 | Characteristics of in-site chamber group

The plastic zone area, roof subsidence and vertical stress of the in-site chamber group are shown in Figure 11. The vertical stress monitoring curve and the vertical displacement monitoring curve of the rock-coal pillar are shown in Figure 12.

As shown in Figure 11A, the plastic zone of the chamber group is relatively developed due to the deep mining conditions and the super-large sectional of the chamber. The maximum failure depth of two sides of the SWM chamber is to 10 m, and the maximum failure depths of two sides of the SC chamber, the SPT chamber and the DSS chamber are 9 m. The maximum failure depth of the chamber group roof and floor is 11.0 m and 13.0 m, respectively. In addition, there are also some differences in the surrounding rock at the chamber group intersections. Marking the 4 chamber group intersections as A, B, C and D, the maximum failure radius at intersection A and C is 12.0 m, that at intersection B is 14.2 m, and at intersection D is 12.4 m. As shown in Figure 11B, the roof subsidence reaches the maximum at the chamber group intersection, and the maximum roof subsidence, which is 75.4 mm, appears at intersection C. As shown in Figure 11C, the stress concentration area appears at the chamber group intersection for the stress redistribution caused by chamber group excavation, and the maximum vertical stress is 48.4 MPa. The stress monitoring curve (Figure 12A) shows that the stress concentration area is approximately 10 m away from intersection C, and the maximum vertical displacement at the rock-coal pillar is 181.0 mm, as shown in Figure 12B.

According to the figures, the maximum vertical stress of the coal gangue separation chamber group in the Longgu Coal Mine is approximately 10 m away from the intersection, which is 48.6 MPa. The vertical displacement of the rock-coal pillar surrounded by the chamber group is 181.0 mm. The maximum deformation of the surrounding rock is located at the roof of the chamber group intersection, which is 75.4 mm; the maximum failure radius of the surrounding rock is located at intersection B, which is 14.2 m. Therefore, the surrounding rock at the chamber group intersection is affected by high ground stress and repeated excavation disturbance, which makes stress concentration more complex and the maximum vertical stress larger. In addition, stress concentration
causes the surrounding rock to exceed its ultimate strength, which intensifies the degree of failure, enlarges the scope of the failure and makes the surrounding rock deformation more intense. The roof subsidence and the plastic zone radius at the chamber group intersection are obviously larger than the roof subsidence and the plastic zone radius of other parts of the chamber groups, which increased by approximately 50.8% and 44.4%, respectively. In addition, the interaction between the chambers is more severe, and the radius of the plastic zone is the largest at the intersection B for the smaller angle of the SC chamber and the SWM chambers. Therefore, the chamber group intersection should be the key area of control of the surrounding rock, and the integrity of the intersection affects the overall stability of the chamber group.

Statistical analysis of the existing medium and large section chamber/roadway (Table 3) shows that the chamber/roadway depth is positively correlated with the maximum vertical stress, deformation, and failure of the surrounding rock under the similar cross section. When the buried depth is similar, the cross section determines the stress and

FIGURE 8 The simulation schemes of chamber group spacing and the monitoring points arrangement. (A) Spacing 100 m; (B) Spacing 90 m; (C) Spacing 80 m; (D) Spacing 70 m; (E) Spacing 60 m; (F) Spacing 50 m; (G) Spacing 40 m; (H) Spacing 30 m; (I) Spacing 20 m
deformation of the surrounding rock, which means the larger the cross section, the more severe deformation and failure of the surrounding rock. Comparing the simulation results of the in-site chamber group with the existing medium and large section chamber/roadway, the surrounding rock failure range of the deep super-large section chamber is larger, the surrounding rock deformation is more severe, and the maximum vertical stress is higher during excavation.

4.2 | Determination of key parameters

4.2.1 | Chamber group spacing

The numerical simulation of the plastic zone and the vertical displacement for different chamber group spacings are shown in Figures 13-15. The rock-coal pillar vertical displacement monitoring curve and maximum vertical stress monitoring curve are shown in Figure 16. With the chamber group spacing decrease, the stress, displacement, and plastic zone area of the surrounding rock increased to varying degrees.

When the chamber group spacing is 100-80 m, the surrounding rock of the chamber group develops a large range of the plastic zone due to the large burial depth and cross section. The maximum failure depth of two sides is 9 m, and the maximum failure depth of the roof and the floor are 12.0 m and 13.0 m, respectively. Moreover, the maximum failure radius at the intersection of the chamber group is 11 m. With the decrease in the chamber spacing, the maximum failure radius of the surrounding rock remains basically unchanged, and the plastic zone area increases slightly. The maximum

![Figure 9](image-url)
roof deformation is located at the chamber intersection, and the subsidence increases slightly from 69.9 mm to 72.7 mm. The deformation of the rock-coal pillar increases slightly, from 130.9 mm to 142.3 mm. The stress of the surrounding rock of the chamber group is redistributed, and the stress concentration area is located approximately 10 m from the chamber intersection. As the spacing decreases, the maximum vertical stress increases slightly from 44.2 MPa to 44.9 MPa. Therefore, there appears to be no interaction in the surrounding rock of the chamber group when the spacing is larger than 80 m.

When the chamber group spacing decreases from 80 m to 50 m, the maximum failure depth of the chamber two sides increases slightly, but the maximum failure depth of the roof and floor obviously increases, which is 14 m and 15 m, respectively. The failure range of the surrounding rock is obviously larger, and there is a tendency for mutual penetration at the floor. The maximum failure radius at the intersection increases to 13 m. The subsidence and deformation range of the roof obviously increased, and the maximum subsidence increased from 72.7 mm to 84.6 mm. In addition, the deformation of the rock-coal pillar is more obvious. According to the monitoring curve, the vertical displacement of the rock-coal pillar increases from 142.3 mm to 240.0 mm with the decrease in the chamber spacing. The maximum vertical stress of the surrounding rock also increases greatly, from 44.9 MPa to 49.0 MPa. At that point, there is an interaction between the chamber group. The stresses begin to superimpose on each other, leading to the maximum roof subsidence and deformation range at the intersection increasing significantly. The plastic zone area of the surrounding rock increases greatly, and there is a trend of mutual penetration. The first impact position is the middle floor surrounding rock.

As chamber group spacing continues to decrease, the interaction is further enhanced, the plastic zone area continues to increase, and the degree of failure is gradually intensified. When the spacing between chamber groups decreases from 50 m to 20 m, the plastic penetration zone of the surrounding rock transfers from the floor to the roof and then penetrates completely. Serious deformation and failure occur at the chamber group roof, and the maximum plastic zone radius reaches 17 m. The maximum roof subsidence range gradually covers the entire chamber group roof from the intersection, and the maximum subsidence increases from 84.6 mm to 138.7 mm. Furthermore, when the chamber group spacing is 20 m, the chamber group surrounding rock loses its bearing capacity and cannot continue to bear the overlying strata load due to the complete penetration of the plastic zone. The plastic zone transfers to the deep intact rock mass of the chamber group. Therefore, the maximum vertical stress of the surrounding rock of the chamber group suddenly decreases, and the vertical displacement of the rock-coal pillar first increases and then decreases before gradually stabilizing at a spacing of 20 m.

The relationship of the plastic zone area, the maximum roof subsidence, the rock-coal pillar vertical displacement, and the maximum vertical stress with chamber group spacing.
is calculated, as shown in Figure 17. The figures show that when the spacing is 80 m, the plastic zone area increases by 3.1%, the maximum roof subsidence increases by 4.0%, the rock-coal pillar vertical displacement increases by 8.7% and the maximum vertical stress increases by 1.6% compared with the spacing of 100 m, which shows that there is hardly any mutual interaction when the chamber group spacing decreases from 100 m to 80 m, and the surrounding rock
remains intact and stable. When the spacing decreases from 80 m to 70 m, the plastic zone area increases by 7.1%, the maximum roof subsidence increases by 7.7%, the rock-coal pillar vertical displacement increases by 7.7%, and the maximum vertical stress increases by 3.6%. Thus, when the spacing is 70 m, the increase range is obviously increased, and chamber groups begin to interact with each other. When the chamber group spacing decreases to 30 m, the plastic zone area increases by 55.9%, the maximum roof subsidence increases by 45.9%, the rock-coal pillar vertical displacement increases by 139.0%, and the maximum vertical stress increases by 32.1% compared with the spacing of 80 m. At this point, the interaction of the chamber groups is intense, leading to the instability failure in the surrounding rock. When chamber group spacing is 20 m, the plastic zone area and the maximum roof subsidence continue to increase, 18.0% and 30.7% higher than the plastic zone area and the maximum roof subsidence of 30 m. However, due to the complete penetration of the plastic zone into the surrounding rock, the coal pillar loses its bearing capacity and cannot support the overlying strata load. Therefore, the vertical displacement and the maximum vertical stress of the rock-coal pillar decrease. Therefore, the optimal spacing of the chamber group can be determined to be 80 m.

The plastic zone area and the maximum roof subsidence are fitted by function, respectively. With the chamber group spacing decrease, the plastic zone area increases parabolically, conforming to the quadratic polynomial relationship. The maximum roof subsidence increases exponentially, conforming to the exponential relationship. The correlation coefficient squares ($R^2$) are both greater than .99. Then, the rock-coal pillar vertical displacement and the maximum vertical stress without spacing 20 m are fitted. The rock-coal pillar vertical displacement and the maximum vertical stress increase exponentially with the decrease in the chamber spacing, both in accordance with the exponential relationship, and $R^2$ is greater than .99.

4.2.2 | Chamber group angle

The numerical simulation of the plastic zone and the vertical displacement for different chamber group angles are shown in Figures 18 and 19. The rock-coal pillar vertical displacement monitoring curve and maximum vertical stress monitoring curve are shown in Figure 20.

The figures show that when the chamber group angle is 85°-70°, the plastic zone radius at the intersection is larger than other parts of the chamber group and shows a growth trend. To be precise, the maximum plastic zone radius at intersection A, C, and D is slightly increased from 12.0 m to 13.2 m. The failure at intersection B is more obvious, where the maximum plastic zone radius increases from 12.7 m to 15.3 m. Roof deformation decreases with chamber group angle reduction. The maximum roof subsidence occurs at chamber intersection C, from 78.0 mm to 74.6 mm. The minimum roof deformation occurs at chamber intersection B, from 75.0 mm to 70.0 mm. The monitoring result of the rock-coal pillar vertical displacement shows that the deformation decreases from 213.4 mm to 168.4 mm. Moreover, the stress monitoring result of the surrounding rock shows that the stress concentration area is approximately 10 m away from intersection A. The maximum vertical stress decreases from 50.8 MPa to 47.9 MPa with the decrease of the chamber group angle. Therefore, when the chamber group angle is 85°-70°, the rock-coal vertical displacement, the maximum vertical stress, and the maximum roof subsidence are reduced to different extents, and the maximum plastic zone radius is gradually increased.

FIGURE 12 Simulation monitoring curve for in-site chamber group. (A) Vertical stress; (B) Vertical displacement of rock-coal pillar
When the chamber group angle is 70°-50°, the plastic zone radius at the intersection continues to increase, and the maximum plastic zone radius at intersection D increases slightly from 12.7 mm to 15.0 mm. The increase at intersection B is most pronounced, from 15.3 m to 22.4 m. The deformation of the rock-coal pillar is further reduced, from 168.4 mm to 141.7 mm. Roof deformation shows different trends with chamber group angle decrease. The roof subsidence at intersection C increases from 74.6 mm to 78.6 mm, while the roof subsidence at intersection B continues to decrease from 70.0 mm to 60.0 mm. The stress concentration area is still located approximately 10 m away from intersection A, and the maximum vertical stress increases with chamber group angle decrease, from 47.9 MPa to 50.5 MPa. Therefore, when the chamber group angle is 70°-50°, the maximum plastic zone radius, the maximum vertical stress and the maximum roof subsidence increase in varying degrees, and the rock-coal pillar vertical displacement is further reduced.

The relationship of the maximum plastic zone radius at the intersection, the rock-coal pillar vertical displacement, the maximum roof subsidence and the maximum vertical stress with the chamber group angle are counted, as shown in Figure 21. With the chamber group angle decrease, the maximum plastic zone radius increases continuously. Compared with the angle of 85°, the maximum plastic zone radius is increased by 76.4%, and the rock-coal pillar vertical displacement decreases by 33.6% at an angle of 50°. The maximum plastic zone radius and the rock-coal pillar vertical displacement are fitted by function, respectively (Figure 21A). The maximum plastic zone radius at the intersection increases approximately parabolically with the decrease in the chamber group angle, which conforms to the quadratic polynomial relationship. In addition, the rock-coal pillar vertical displacement decreases approximately parabolically, which conforms to the quadratic polynomial relationship as well. The $R^2$ are both greater than .98. As shown in Figure 21B, the maximum vertical stress and the maximum roof subsidence first decrease and then increase. Compared with the angle of 85°, the maximum vertical stress decreases by 5.7% and the maximum roof subsidence decreases by 4.6% at the angle of 70°. When the angle is reduced to 50°, the maximum vertical stress increases by 5.4% and the maximum roof subsidence increases by 5.5% compared with the angle of 70°. Based on the above analysis, the optimal angle of the chamber group can be determined to be 70°.

### 4.3 Verification and optimization

According to the chamber group parameters determined by the above research, the optimal chamber group parameters are compared with the in-site parameters, as shown in Figure 22. The maximum roof subsidence is reduced from 75.4 mm to 74.6 mm, the maximum vertical stress is reduced from...
FIGURE 13  Vertical view of plastic zone for different chamber group spacings. 
(A) Spacing 100 m; (B) Spacing 90 m; 
(C) Spacing 80 m; (D) Spacing 70 m; 
(E) Spacing 60 m; (F) Spacing 50 m; 
(G) Spacing 40 m; (H) Spacing 30 m; (I) Spacing 20 m
48.4 MPa to 47.9 MPa, and the rock-coal pillar vertical displacement is reduced from 181.0 mm to 168.4 mm. In addition, the maximum plastic zone radius is slightly increased, from 14.2 m to 15.3 m because the area of the rock-coal pillar increases with the decrease in the chamber group angle, which plays an effective supporting role on the overlying strata. In addition, the interaction between two adjacent chambers intensifies, which causes the surrounding rock at the intersection B to exceed its ultimate strength and leads eventually to large-scale failure. The field application effect of a super-large section chamber group for coal gangue separation system in the Longgu Coal Mine is shown in Figure 23. The roof deformation is small, and the surrounding rock of the chamber group is relatively intact, which can meet the normal production needs.

The research results show that the in-site chamber group spacing is the optimum, and the chamber group angle can continue to be optimized, not only further reducing the peak stress and deformation of the surrounding rock of the chamber group but also effectively reducing the excavation quantity and postmaintenance workload. This study provides guidance and reference for the layout design of the chamber group under the same or similar geological conditions.

5 | DISCUSSION

In this paper, the authors revealed the failure evolution for a super-large section chamber group in a deep coal mine and determined the optimal spacing and angle.
FIGURE 15 Contour of vertical displacement for different chamber group spacings. (A) Spacing 100 m; (B) Spacing 90 m; (C) Spacing 80 m; (D) Spacing 70 m; (E) Spacing 60 m; (F) Spacing 50 m; (G) Spacing 40 m; (H) Spacing 30 m; (I) Spacing 20 m
**FIGURE 16** Simulation monitoring curve for different chamber group spacings. (A) Vertical displacement of rock-coal pillar; (B) Maximum vertical stress

(A) Vertical displacement of rock-coal pillar

(B) Maximum vertical stress

**FIGURE 17** Simulation results statistical curve for different chamber group spacings. (A) Plastic zone area; (B) Maximum vertical stress; (C) Vertical displacement of rock-coal pillar; (D) Maximum vertical stress

(A) Plastic zone area

(B) Maximum roof subsidence

(C) Vertical displacement of rock-coal pillar

(D) Maximum vertical stress
Currently, some scholars focus on medium and large section chambers under shallow or medium burial depth to obtain the failure evolution and influencing factors of the surrounding rock of a chamber group under specific geological and mining conditions, which provides some support for the stability control. However, there are few studies on deep super-large section chamber groups, and the research on the spacing and angle of the chamber group is also scarce. In this paper, the authors reveal the failure evolution and characteristics of the surrounding rock for a deep super-large section chamber group and find that the intersection area of the chamber group is the key area for controlling the overall chamber group, providing a solid foundation for the support design. Moreover, chamber groups with different spacings and angles were simulated separately, and the influences on the stress, deformation, and failure evolution of the surrounding rocks were obtained. On this basis, the optimal spacing and angle were determined. This study provides guidance and reference for the design of a super-large section chamber group construction under the same or similar conditions and its surrounding rock control strategy.

We adopt the controlling variables method in the optimal chamber group parameter determination, which can make the simulation schemes more pertinent, but it also has limitations to a certain extent. Moreover, we obtained the optimal spacing and angle of the chamber group by numerical simulation but did not obtain a quantitative analytical solution theoretically. In future work, we will further establish the corresponding mechanical model to reveal the instability mechanism of surrounding rock to make it more widely acceptable.

6 CONCLUSIONS

The aim of this research was to improve the stability of super-large section chamber group in a deep coal mine by studying
the failure evolution of surrounding rocks and determining its optimal key parameters. Compared with the current published works, this work has at least two original aspects:

1. The surrounding rock stress, deformation, and failure evolution for an in-site chamber group were revealed, and the critical area for controlling the stability of the chamber group was found to be the intersection area.

2. The influences of two key parameters, spacing and angle, on the surrounding rock stability of a deep super-large section chamber group were studied, and the optimal spacing and angle were determined.

Numerical simulations showed that the stress concentration, plastic zone and deformation of the surrounding rocks of coal gangue separation system are much larger than those of other
**FIGURE 20** Simulation monitoring curve for different chamber group angles. (A) Vertical displacement of rock-coal pillar; (B) Maximum vertical stress

**FIGURE 21** Simulation results statistical curve for different chamber group angles. (A) Maximum plastic zone radius and vertical displacement of rock-coal pillar; (B) Maximum vertical stress and roof subsidence

**FIGURE 22** Comparison of in-site parameters and optimal parameters
medium or large section chambers/roadways. Moreover, the roof subsidence and plastic zone radius at the intersection are approximately 50.8% and 44.4% larger than those of other parts for the superimposed stress and repeated excavation disturbance.

Additionally, with the spacing decreasing from 100 m to 20 m, the plastic zone area, roof subsidence, and vertical stress remain constant first and increase significantly since the spacing is smaller than 80 m. With the angle decreasing from 85° to 50°, the vertical stress and roof subsidence first decrease and then increase, and they all reach the minimum at the angle of 70°. Compared with the actual parameters, the spacing is the optimum, but the angle can be further optimized. Field application observations verifies this conclusion.

It should be noted that we did not obtain a quantitative analytical solution from the theoretical perspective in this work. In future work, we will further establish the corresponding mechanical model to study the instability mechanism of chamber group surrounding rock.

ACKNOWLEDGMENTS
The authors gratefully acknowledge the financial support from the National Key R&D Program of China (No. 2018YFC0604703), National Natural Science Foundation of China (Nos. 51804181, 51874190, and 51574154), Major Program of Shandong Province Natural Science Foundation (No. ZR2018ZA0603), Key R&D project of Shandong Province (No. 2019GSF111020), Shandong Province Natural Science Fund (No. ZR2018QEE002), Open Fund of State Key Laboratory of Water Resource Protection and Utilization in Coal Mining (No. QJNY-18-73.5), Tai’shan Scholar Engineering Construction Fund of Shandong University of Science and Technology for Recruited Talents (No. 2017RCJJ008).

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Yunliang Tan, Deyuan Fan, and Xuesheng Liu equally contributed to this work; Deyuan Fan and Xuesheng Liu conceived and designed this paper; Yunliang Tan amended this paper; Xuesheng Liu wrote “Introduction” of this paper; Deyuan Fan wrote the other parts of this paper; Shilin Song, Li Xianfeng and Wang Honglei helped to review this paper.

ORCID
Deyuan Fan https://orcid.org/0000-0001-9844-1960

REFERENCES
1. Qian MG, Xu JL, Wang JC. Further on the sustainable mining of coal. J China Coal Soc. 2018;43:1-13.
2. Li M, Zhang JX, Zhou N, Huang YL. Effect of particle size on energy evolution of crushed waste rock in coal mines. Rock Mech Rock Eng. 2017;50:1347-1354.
3. Wang Q, Li RR. Journey to burning half of global coal: trajectory and drivers of China’s coal use. Renew Sust Energ Rev. 2016;58:341-346.
4. Si H, Bi HP, Li XH, Yang CH. Environmental evaluation for sustainable development of coal mining in Qijiang, Western China. Int Coal Geol. 2016;81:163-168.
5. Huang J, Tian C, Xing L, Bian Z, Miao X. Green and sustainable mining: underground coal mine fully mechanized solid dense stowing-mining method. Sustainability. 2017;9:1418.
6. Cui CB, Jiang SG, He XJ, Wang K, Shao H, Wu ZY. Experimental study on the location of gas drainage pipeline leak using cellular automata. J Loss Prevent Proc. 2018;56:68-77.
7. Knappstein R, Kuenne G, Becker LG, et al. Large eddy simulation of a novel gas-assisted coal combustion chamber. Flow, Turbal Combust. 2018;101:895-926.
8. Li M, Aminossadati SM, Wu C. Numerical simulation of air ventilation in super-large underground developments. Tunn Undergr Space Technol. 2016;52:38-43.
9. Zhang GC, Liang SJ, Tan YL, Xie FX, Chen SJ, Jia HG. Numerical modeling for longwall pillar design: a case study from a typical longwall panel in China. J Geophys Eng. 2019;16:666.
10. Zhu W, Xu J, Li Y. Mechanism of the dynamic pressure caused by the instability of upper chamber coal pillars in Shendong coalfield, China. Geosci J. 2017;21:729-741.
11. Ajrash MJ, Zanganeh J, Moghtaderi B. Methane-coal dust hybrid fuel explosion properties in a large scale cylindrical explosion chamber. *J Loss Prevent Proc*. 2016;40:317-328.

12. Wang M, Zheng DJ, Niu SJ, Li WF. Large deformation of tunnels in longwall coal mines. *Environ Earth Sci*. 2019;78:45.

13. Chen SJ, Yin DW, Liu XY, Wang HL, Cao FW, Pu ZQ. Collaborative mining using different equipment for a coal seam varying in thickness in a long wall working face. *Int J Oil Gas Coal T*. 2016;13:73-86.

14. Yang RS, Xue HJ, Guo DM, Li YL, Li TT, Xue JZ. Failure mechanism of surrounding rock of large section chambers in complex rock formations and its control. *J China Coal Soc*. 2015;40:2234-3224.

15. Chen GZ, Wang JJ, Bao JS. Anti-explosion impulsive behaviors of the coal mine refuge chamber's cabin. *J China Soc Mech Eng*. 2017;38:155-163.

16. Zhang BY, Zhai DX, Wang W. Failure mode analysis and dynamic response of a coal mine refuge chamber with a gas explosion. *Appl Sci*. 2016;6:145.

17. Kong B, Wang EY, Li ZH, Lu W. Study on the feature of electromagnetic radiation under coal oxidation and temperature rise based on multi-fractal theory. *Fractals*. 2019;27:1950038.

18. Chen J, Jiang Q, Feng XT, Hu YR. Intelligent back analysis of rock mass creep parameters for large underground caverns under high in-situ stress based on incremental displacement. *J China Coal Soc*. 2019;44:1446-1455.

19. Fan DY, Liu XS, Tan YL, et al. Roof cutting parameters design for gob-side entry in deep coal mine: a case study. *Energies*. 2019;12:2032.

20. Qi K, Tan ZY, Li W. Stability analysis on the crossed cavern group in underground mine. *Min R D*. 2017;37:52-55.

21. He MC, Li GF, Ren AW, Yan J. Analysis of the stability of intersecting chambers in deep soft-rock roadway construction. *J China Univ Min Tech*. 2008;37:167-170.

22. Lin HL, Shi YK. Simulation on stability of surrounding rock of large section chambers in deep structural complex areas. *J China Coal Soc*. 2011;36:1619-1623.

23. Cheng H, Cai HB, Rong CX, Yao ZS, Li MJ. Rock stability analysis and support countermeasure of chamber group connected with deep shaft. *J China Coal Soc*. 2011;36:261-266.

24. Sun XM, Wang D, Miao CY, Li Y, Xu HC. Research on dynamic pressure instability mechanism and control countermeasure of deep pump room and chamber group in Nantun Coal Mine. *J China Coal Soc*. 2015;40:2303-2312.

25. Wang QZ, Xie WB, Jing SG, Fei XB. Instability mechanism and control technology of chamber group surrounding rock in complex structural area. *J Min Saf Eng*. 2014;31:263-269.

26. Chen SJ, Qa X, Yin DW, Liu XQ, Ma HF, Wang HY. Investigation lateral deformation and failure characteristics of strip coal pillar in deep mining. *Geomech Eng*. 2018;14:421-428.

27. Meng FZ, Wong L, Zhou H, Yu J, Cheng GT. Shear rate effects on the post-peak shear behaviour and acoustic emission characteristics of artificially split granite joints. *Rock Mech Rock Eng*. 2019;52:1-20.

28. Fang K, Zhao TB, Zhang YB, Qiu Y, Zhou JH. Rock cone penetration test under lateral confining pressure. *Int J Rock Mech Min*. 2019;119:149-155.

29. Li SH, Zhu WC, Niu LL, Yu M, Chen CF. Dynamic characteristics of green sandstone subjected to repetitive impact loading: phenomena and mechanisms. *Rock Mech Rock Eng*. 2018;51:1921-1936.

30. Gao MS, Zhao HC, Zhao YC, Gao XJ, Wang XY. Investigation on the vibration effect of shock wave in rock burst by in situ microseismic monitoring. *Shock Vib*. 2018;2018:1-14.

31. Zhai XX, Huang GS, Chen CY, Li RB. Combined supporting technology with bolt-grouting and floor pressure-relief for deep chamber: an underground coal mine case study. *Energies*. 2018;11:67.

32. Yang RS, Ding CX, Yang LY, Zhang YF, Xu P. Behavior and law of crack propagation in the dynamic-static superimposed stress field. *J Test Eval*. 2018;46:2540-2548.

33. Ning JG, Liu XS, Tan J, et al. Control mechanisms and design for a 'coal-backfill-gangue' support system for coal mine gob-side entry retaining. *Int J Oil Gas Coal T*. 2018;18:444-466.

34. Li Y, Zhang S, Zhang X. Classification and fractal characteristics of coal rock fragments under uniaxial cyclic loading conditions. *Arab J Geosci*. 2018;11:201.

35. Huang WP, Yuan Q, Tan YL, et al. An innovative support technology employing a concrete-filled steel tubular structure for a 1000-m-deep roadway in a high in situ stress field. *Tunn Undergr Sp Technol*. 2018;73:26-36.

36. Liu XS, Ning JG, Tan YL, Gu QH. Damage constitutive model based on energy dissipation for intact rock subjected to cyclic loading. *Int J Rock Mech Min Sci*. 2016;85:27-32.

37. Liu XS, Ning JG, Tan YL, Gu QH. Coordinated supporting method of gob-side entry retaining in coal mines and a case study with hard roof. *Geomech Eng*. 2018;15:1173-1182.

38. Liu XS, Tan YL, Ning JG, Lu YW, Gu QH. Mechanical properties and damage constitutive model of coal in coal-rock combined body. *Int J Rock Mech Min*. 2018;110:140-150.

39. Zhao TB, Guo WY, Tan YL, Yin YC, Cai LS, Pan JF. Case studies of rock bursts under complicated geological conditions during multi-seam mining at a depth of 800m. *Rock Mech Rock Eng*. 2018;51:1539-1564.

40. Tan YL, Liu XS, Ning JG, Tian CL. Front abutment pressure concentration forecast by monitoring cable-forces in the roof. *Int J Rock Mech Min Sci*. 2015;77:202-207.

41. Guo WY, Tan YL, Yu FH, et al. Mechanical behavior of rock-coal-rock specimens with different coal thicknesses. *Geomech Eng*. 2018;15:1017-1027.

42. Wang J, Ning JG, Jiang QJ, Bu TT. Structural characteristics of strata overlying of a fully mechanized longwall face: a case study. *J Afr I Min Metall*. 2018;118:1195-1204.

43. Jiang BY, Gu ST, Wang LG, Zhang GC, Li WS. Strainburst process of marble in tunnel-excavation-induced stress path considering intermediate principal stress. *J Cent South Univ*. 2019;26:984-999.

44. Tan YL, Liu XS, Shen B, Gu QH, Ning JG. New approaches to testing and evaluating the rockburst risk of coal seam with hard roof and/or floor in coal mines. *Geomech Eng*. 2018;14:367-376.

45. Li WT, Yang N, Yang B, et al. An improved numerical simulation approach for arch-bolt supported tunnels with large deformation. *Tunn Undergr Sp Technol*. 2018;77:1-12.

46. Li WT, Li SC, Xuan C, Wand Q, Wang X, Shao X. Mechanism and control of failure of roof roadway supported in highly stressed soft rock. *Chin J Rock Mech Eng*. 2015;34:1836-1848.

47. Qian DY, Zhang N, Pan DJ, et al. Stability of deep underground openings through large fault zones in argillaceous rock. *Sustainability*. 2017;9:2153.
49. Sun Q, Zhang JX, Zhang Q, Yan H. A case study of mining-induced impacts on the stability of multi-tunnels with the backfill mining method and controlling strategies. Environ Earth Sci. 2018;77:234.

50. Feng XT, Haimson B, Li XC, et al. ISRM suggested method: determining deformation and failure characteristics of rocks subjected to true triaxial compression. Rock Mech Rock Eng. 2019;52:2011-2020.

51. Kang H, Zhang X, Si L, Wu Y, Gao F. In-situ stress measurements and stress distribution characteristics in underground coal mines in China. Eng Geol. 2010;116:333-345.

52. Tan YL, Gu QH, Ning JG, Liu XS, Jia ZC, Huang DM. Uniaxial compression behavior of cement mortar and its damage-constitutive model based on energy theory. Materials. 2019;12:1309.

53. Alejano LR, Muralha J, Ulusay R, et al. ISRM suggested method for determining the basic friction angle of planar rock surfaces by means of tilt tests. Rock Mech Rock Eng. 2018;52:3853-3859.

54. Liu XS, Gu QH, Tan YL, Ning JG, Jia ZC. Mechanical characteristics and failure prediction of cement mortar with a sandwich structure. Minerals. 2019;9:143.

55. Ishida T, Labuz JF, Manthei G, et al. ISRM suggested method for laboratory acoustic emission monitoring. Rock Mech Rock Eng. 2017;50:665-674.

56. Zhang K, Cao P, Meng JI, Li KH, Fan WC. Modeling the progressive failure of jointed rock slope using fracture mechanics and the strength reduction method. Rock Mech Rock Eng. 2015;48:771-785.

57. Shen J, Karakus M. Three-dimensional numerical analysis for rock slope stability using shear strength reduction method. Can Geotech J. 2014;51:164-172.

58. Chen SJ, Yin DW, Cao FW, Liu Y, Ren KQ. An overview of integrated surface subsidence-reducing technology in mining areas of China. Nat Hazards. 2016;81:1129-1145.

59. Yin YC, Zhao TB, Zhang YB, et al. An innovative method for placement of gangue backfilling material in steep underground coal mines. Minerals. 2019;9:107.

60. Qiu C, Wang XF, Long EP, Liu F. Numerical simulation analysis of failure characteristics of surrounding rock in deep tunnel. Coal Tech. 2014;33:143-145.

61. Ning JG, Wang J, Jiang JQ, Hu SC, Jiang LS, Liu XS. Estimation of crack initiation and propagation thresholds of confined brittle coal specimens based on energy dissipation theory. Rock Mech Rock Eng. 2018;51:119-134.

62. Guo DM, Wang CG, Wu YY, Hou J, Liu K, Xue JH. Surrounding rock failure mechanism and technology of grouting reinforcement in winch chamber. Coal Sci Tech. 2014;42:27-30.

63. Guo JW. Roadway fracture mechanism and control technology of joint fissured surrounding rock in deep mines. J China Coal Soc. 2012;37:1559-1563.

64. Ma Q, Tan YL, Zhao ZH, Xu Q, Wang J, Ding K. Roadside support schemes numerical simulation and field monitoring of gob-side entry retaining in soft floor and hard roof. Arab J Geosci. 2018;11:563.

65. Booth AJ, Marshall AM, Stace R. Probabilistic analysis of a coal mine roadway including correlation control between model input parameters. Comp Geotech. 2016;74:151-162.

66. Piotr P, Andrzej K, Andrzej W. Numerical simulation of subsidence caused by roadway system. Arch Min Sci. 2019;64(2):385-397.