INTRODUCTION

Longwall mining is the most widely used method for exploiting coal in China, and many coal pillars usually occur within a mine. The size of a chain pillar is typically 4-50 m.\textsuperscript{1-3} Many irregular residual coal pillars are unavoidably left on the boundary of the mining area due to the mining conditions, and the pillars are typically 10-200 m in size.\textsuperscript{4}
When mining in close-distance coal seams, the longwall faces in the upper and lower coal seams are typically parallel. However, due to the effects of faults, coal thickness changes, and other factors, the longwall faces in the upper and lower coal seams are not parallel. Hence, the longwall face or gateroad in the lower coal seam may be located in the lower part of the residual coal pillars in the upper coal seam. Because of the small distance between the coal seams (<20 m), the concentrated stress that is transmitted by the residual coal pillars in the upper coal seam will inevitably result in difficulties with longwall face mining and gateroad support in the lower coal seam.5,6

During the mining process of close-distance coal seams, the loading of the residual coal pillar in the upper coal seam and the law of downward transmission of the residual coal pillar loading must be determined. According to the tributary area theory, which has achieved a consensus among academics, coal pillar loading is calculated based on the assumption that the coal pillar bears the loading of the overlying stratum within its influenced area.7 Using this category, the stability analysis method of coal pillars8 and the Wilson and Carr9 method are developed. These methods mainly calculate the loading of a regular coal pillar; however, it is difficult to use these methods to calculate the loading of a residual irregular coal pillar. The high stress that is caused by mining in the upper coal seam propagates to the floor.10,11 The calculation of the stress distribution law of the floor depends mainly on elastic-plastic mechanics,12 and calculating the floor stress distribution of an irregular residual coal pillar that remains in the upper coal seam is more difficult via these methods.

Another key step is determining the chain pillar strength. Formulæ to determine the coal pillar strength have been proposed by various academics via numerical, analytical, and empirical studies.13,14 By using the method of maximum likelihood, Munro and Salamon15 presented an empirical formula of the coal pillar strength. By using the overlap reduction technique, Van16 introduced an alternative formula for the calculation of coal pillar strength, and through direct strength tests of coal pillars of different sizes, Bieniawski17 obtained a formula for coal pillar strength. The above formulæ assume that the loading distribution on a coal pillar is uniform; however, this is typically not the case.18,20

Over the past decades, FLAC3D software has been commonly used in longwall mining to investigate mining-induced rock mass responses. Li21 studied the distribution of surrounding rock stress in slice mining and top-coal caving mining in thick coal seams by performing FLAC3D numerical simulations, and the effects of load shedding and rock-burst reduction of top-coal caving mining were summarized. Mo22 quantified the effect of backfilling on pillar strength in highwall mining via numerical modeling. Gao23 combined the finite element method and the finite difference method to analyze the effects of directional roof split blasting on the stability of the entry surroundings. The three-dimensional finite difference technique was used by Basarir24 to predict stress changes around gateways and coal pillars in a top-coal caving panel.

In this paper, parts of the chain pillar and gateroad in the lower coal seam were located at the lower part of the irregular residual coal pillar that remained in the upper coal seam. In the process of lower coal seam mining, part of the residual coal pillar was destroyed and the size of the residual coal pillar was reduced, which resulted in gateroad collapse and chain pillar failure in the lower coal seam.

Methods such as field surveys, roof movement measurement, vertical stress change monitoring, and numerical simulation analyses have been used to analyze gateroad system failure caused by irregular residual coal pillars in upper coal seams, and the mechanisms underlying gateroad system failure have been clarified.

2  |  GEOLOGY AND GATERoad FAILURE

2.1  |  Introduction to the longwall face

The Gaojialiang mine is located in the western Ordos City, Inner Mongolia, China. A 2-2coal seam, a 2-2 coal seam, a 3 coal seam, and a 5 coal seam are available in the mine. The 2-2 coal seam has been mined, and the 2-2 coal seam is being mined, whereas the other coal seams have not yet been mined. The 2-2 coal seam and the 2-2 coal seam were formed in the Jurassic period, and the gas content of the two coal seams is low at approximately 1 m³/t.

The thickness of the 2-2 coal seam in the mine is 3.2-4.0 m, with an average value of 3.5 m, and the average dip is 3°. The roof of the longwall faces in the 2-2 coal seam was managed by caving. In the 2-2 coal seam, the P20111, P20112, P20113, and P20120 longwall faces stopped retreating in 2012, 2013, early 2016, and the end of 2016, respectively. The irregular residual coal pillar (S1 coal pillar) was formed after the four longwall faces were mined as illustrated in Figure 1.

According to geological exploration bores in panel section 203, the thickness of the 2-2 coal seam is 3.1-3.6 m, with an average value of 3.3 m. The average dip of the 2-2 coal seam is 3° at the area of interest, with an average depth of 170 m. The sandy mudstone between the 2-2 coal seam and the 2-2 coal seam has an average thickness of 5.0 m. The strata above the 2-2 coal seam are mudstone (average thickness is 9.8 m) and fine sandstone (average thickness is 18.2 m). The strata under the 2-2 coal seam are sandy mudstone (average thickness is 9.5 m) and siltstone (average
(A) Roadway layout of panel section 203 in the 2-2 coal seam of the Gaojialiang coal mine

(B) Residual coal pillar in the 2-2 coal seam

FIGURE 1 Roadway layout. (A) Roadway layout of panel section 203 in the 2-2 coal seam of the Gaojialiang coal mine, (B) Residual coal pillar in the 2-2 coal seam
The thickness is 17.7 m. The section of the strata in the area of interest is illustrated in Figure 2.

There are no geological anomalies except for a fault in panel section 203 of the 2-2 coal seam as illustrated in Figure 1(A). The F2 fault is located on the north side of panel section 203, with a vertical throw of 0-16.5 m and a length of 2 km. The distance between the fault and the S1 coal pillar (area of interest) exceeds 600 m. According to field experience, the F2 fault had little influence on the P20314 longwall face excavation.

The P20314 longwall face is the first face in panel section 203 of the 2-2 coal seam. The longwall face is 1750 m in length and 300 m in width. The longwall face also adopts the method of full-seam mining and the roof is managed by caving. A chain pillar with a width of 20 m was designed between the P20314 tailgate and the P20313 headgate.

The P20313 headgate was driven along the roof of the 2-2 coal seam, with a width of 5.2 m and a height of 3.3 m. One side of the headgate was the mining area of the P20313 face; the other side was the chain pillar and the P20314 tailgate. The width of the chain pillar of 20 m was between the P20314 tailgate and the P20313 headgate.

The P20313 headgate was supported by rockbolts and anchor cables with steel mesh and a W-shaped steel strap in the roof. The reinforced support elements were arranged by concrete that was sprayed on the roof. The rockbolts were installed on the two ribs of the headgate and steel mesh, which was accompanied by steel beam, was used as the skin support. The support scheme is illustrated in Figure 3, and the detailed parameters of the support elements are listed in Table 1.

The P20313 headgate was supported by rockbolts and anchor cables with steel mesh and a W-shaped steel strap in the roof. The reinforced support elements were arranged by concrete that was sprayed on the roof. The rockbolts were installed on the two ribs of the headgate and steel mesh, which was accompanied by steel beam, was used as the skin support. The support scheme is illustrated in Figure 3, and the detailed parameters of the support elements are listed in Table 1.

DW35-350/110X hydraulic props were installed in the P20313 headgate under the S1 coal pillar to reinforce the support of the roof before the P20314 longwall face retreated. There were four hydraulic props in each row, with a row spacing of 1000 mm. The support scheme is illustrated in Figure 3.

The P20314 longwall face began to retreat in October 2017 and retreated to the area under the S1 coal pillar in January 2018. When the P20314 longwall face began to retreat, the roof above the S1 coal pillar tended to be stable.25

According to field observations, when the P20314 working face retreated to the area under the P20112 goaf, the deformation of the P20313 headgate under the S1 coal pillar was severe. The severe deformation area of the gateroad was concentrated under part of the S1 coal pillar that is between the P20113 goaf and the P20112 goaf. The P20313 headgate in this area was the research object, and the S1 coal pillar and the area of interest in this paper are illustrated in Figure 1(B).

2.1.2 | Introduction to the P20313 headgate

The P20313 headgate was driven along the roof of the 2-2 coal seam, with a width of 5.2 m and a height of 3.3 m. One side of the headgate was the mining area of the P20313 face; the other side was the chain pillar and the P20314 tailgate. The width of the chain pillar of 20 m was between the P20314 tailgate and the P20313 headgate.

The P20313 headgate was supported by rockbolts and anchor cables with steel mesh and a W-shaped steel strap in the roof. The reinforced support elements were arranged by concrete that was sprayed on the roof. The rockbolts were installed on the two ribs of the headgate and steel mesh, which was accompanied by steel beam, was used as the skin support. The support scheme is illustrated in Figure 3, and the detailed parameters of the support elements are listed in Table 1.

2.2 | Instrumentation in the field

Before the P20314 retreated, measuring stations were arranged in the P20313 headgate under the S1 coal pillar. There were fractured strata (main roof) caused by working face excavation in the 2-2 coal seam. On-site monitoring showed that the fractured position of main roof (fine
sandstone) of P20112 and P20113 faces was 10 m away from the coal wall. The P20313 headgate under the fractured main roof was in a lower stress zone and was less affected by the retreat of the P20314 face. Therefore, obvious changes did not occur in the data monitored by the station installed in this area. Measuring stations should not be arranged under the fractured main roof of the P20112 and P20113 faces, and stations should be separated by a certain distance. The measuring stations of the P20313 headgate are illustrated in Figure 4.

Rock mass movements and vertical stress were measured around the P20313 headgate when the P20314 face was 300 m ahead of the S1 coal pillar.

The following parameters were monitored: (1) the displacement of the roof, (2) the gateroad convergence, and (3) the vertical stress of the chain pillar. Figure 5 illustrates the overall instrumentation in the area of interest.

1. Displacement of the roof

The rock mass movement was recorded by the roof extensometer installed into the P20313 headgate roof. The roof extensometer had 5 anchors, and the distance between the anchors and roof skin was 1, 2, 4, 7, and 10 m respectively.

2. Gateroad convergence

Measuring points are arranged at the measuring stations. The vertical convergence and the horizontal convergence of the P20313 headgate were measured simultaneously using laser rangefinders.

3. Vertical stress changes of the chain pillar

Vertical stress changes within the chain pillar were monitored using hydraulic cells (HCs). At each station, nine hydraulic cells were installed in the chain pillar at various distances from the ribs. The distance between the adjacent hydraulic cells was approximately 0.8 m.

### 2.3 Gateroad failure analysis

According to field observations, when P20314 retreated to the area under the P20112 goaf (at this time, P20314 retreated

| Type     | Primary                          | Reinforced support            |
|----------|----------------------------------|-------------------------------|
| Position | Roof                             | Roof and ribs                 |
| Support elements | Rockbolts | Anchor cables | Rockbolts | Hydraulic props |
                       |                      |                              |              | Concrete spray   |
| Diameter (mm) | 20        | 15.24                  | 20  |                      |
| Length (mm)   | 2200      | 4500                   | 2200|                      |
| Interval (mm) | 800       | 1600                   | 950 |                      |
| Row space (mm)| 800       | 2400                   | 800 | 1000                 |
| Skin support  | Steel mesh, steel beam and W-shaped steel strap | Steel mesh and steel beam | Steel sets |
976 m), the surrounding rock deformation of the P20313 headgate in the area of interest was large as illustrated in Figure 6. The headgate near the #6 measuring station observed a large surrounding rock deformation; then, the same phenomenon was observed near the #5 measuring station.

Because incomplete data were recorded at the #5 measuring station, the surrounding rock deformation of the P20313 headgate at the #6 measuring station was used as an example. According to extent of gateroad failure and surrounding rock deformation rate of P20313 headgate, the process of gateroad failure under the irregular residual coal pillar was divided into three stages as illustrated in Figure 7. The roof movement of the P20313 headgate at the #6 measuring station is shown in Figure 8. The vertical convergence and horizontal convergence are shown in Figure 9.

### 2.3.1 Stage 1

At this stage, the #6 measuring station was in front of the P20314 working face at a distance of 74 m to 10 m. As shown in Figure 9, the main characteristic of the P20313 headgate was skin break. The horizontal convergence of the headgate was stronger than the vertical convergence, and the two rib skins of the P20313 headgate broke into the bulks. The maximum horizontal convergence of the solid rib was 0.16 m, whereas the pillar rib convergence was approximately 0.42 m. The maximum vertical convergence was 0.29 m, with 82.3% contributed by floor heave.

As shown in Figure 8, the first two anchors showed large roof movements, namely, (M1 and M2), which had values of 218 mm and 163 mm, respectively. The displacement of deeper anchors was less than 60 mm; hence, the extent of bedding separation was less than 2 m into the roof.

Figure 10 presents the evolution of vertical stress changes of the chain pillar. Every vertical stress change curve in Figure 10 corresponds to a subfigure in Figure 7. At stage 1, the vertical stress change curve in the chain pillar was saddle shaped when the #6 measuring station was 16 m in front of the P20314 working face. The two peaks of the saddle occurred at 14.3 and 12.9 MPa, and both had distances of 7 m to the ribs.

At this stage, the residual coal pillar (S1 coal pillar) in the upper coal seam is less affected by mining in the lower coal seam and the loading of the S1 coal pillar increased...
constantly. However, the coal bodies on both sides of the P20313 headgate remained stable.

### 2.3.2 Stage 2

As illustrated in Figure 9, at this stage, the #6 measuring station was 10 m in front of and 33 m behind the P20314 face. The horizontal convergence of the pillar rib reached 0.71 m and that of the solid rib increased to 0.31 m, which resulted in a 19.6% width reduction of the P20313 headgate. The maximum vertical convergence was 0.91 m, which was primarily attributed to floor heave (up to 0.55 m). The anchor bolts that were installed into the pillar rib failed, the steel mesh was torn due to the large horizontal movement, and part of the concrete layer in the roof had fallen off.

As illustrated in Figure 8, a sharp increase occurred in the displacement of the first four anchors (M1, M2, M3, and M4), and the displacement of the fourth anchor (M4) increased to 183 mm. The roof separation progressed to 4–7 m into the roof.

According to Figure 10, when the #6 measuring station was 22 m behind the P20314 working face, vertical stress changes formed a unimodal shape curve. The peak value of the vertical stress in the chain pillar suddenly increased to 25.5 MPa from 14.3 MPa, and the average value increased to 14.2 MPa from 8.7 MPa. The chain pillar was subjected to larger loading in this stage than in stage 1. The position of peak vertical stress in the chain pillar remained unchanged, with a distance of 7 m to the rib of the P20314 headgate. The above phenomena indicated that additional loading was applied to the chain pillar.

According to the above phenomena, with the retreat of the P20314 longwall face, the S1 coal pillar in the upper coal seam continued to decrease and the loading that the decreasing S1
coal pillar bore continued to increase. The S1 coal pillar transferred the increased loading to the surrounding rock of the P20313 headgate, which is the main reason for the failure of the coal bodies on both sides of the P20313 headgate.

2.3.3 | Stage 3

As shown in Figure 9, at this stage, the #6 measuring station was behind the P20314 face with a distance of 30 m to 75 m. The roof sagging and floor lift rapidly increased. Severe pillar rib sloughing occurred and led to serious destruction of the chain pillar. The maximum vertical convergence of the headgate reached 2.6 m. The roof sagging was approximately 1.3 m despite the reinforced support. The horizontal convergence of the headgate exceeded 3.04 m, and the deformation...
of the pillar rib reached 2.0 m. Overall, the roof sagging on the side of the pillar rib was larger than that on the side of the solid pillar.

At this stage, due to the serious deformation of the headgate, the roof extensometer at the #6 measuring station was damaged. Therefore, no data on the roof separation were collected at stage 3.

As shown in Figure 10, the vertical stress change curve in the chain pillar essentially changed when the #6 measuring station was 58 m behind the P20314 face. At this time, a vertical stress change curve with double peaks was formed. The values of the two peaks of the stress change curve were 7.7 MPa and 11.6 MPa, and they had distances of 5 m and 7 m to the ribs, respectively. The average vertical stress decreased to 6.2 MPa from 14.2 MPa. The vertical stress change demonstrated that the failure zone had propagated into the entire chain pillar at the #6 measuring station, and the chain pillar was likely in a state of complete failure. Due to above stress change phenomenon, the chain pillar at the 6# measuring station had failed and was in the postpeak state if we consider the chain pillar to have undergone a large compressive test (similar to UCS testing in the laboratory). According to the serious headgate damage compared with those at stage 2, the chain pillar was in a state of strain-softening and the chain pillar strength continued to decrease as the vertical strain quickly increased.

At this time, the hydraulic props at the #6 measuring station in the headgate were almost invalid. According to the tremendous convergence of the P20313 headgate, especially the large roof sagging on the side of the pillar rib, the chain pillar at the 6# measuring station presented yielding. The chain pillar failure further led to the substantial deformation of the headgate and the headgate failure.

3 | FLAC3D MODELING

3.1 | Model setup and calibrations

Based on the P20314 face condition, a FLAC3D model with a size of 2573 m × 1395 m × 105 m was constructed as illustrated in Figure 11. In the software, the extruder function was used to build zones. In the area of interest, the sizes of the zones were approximately 0.5-1.2 m. The zones gradually enlarged away from the area of interest. The horizontal displacement on the side boundaries was fixed. At the base of the model, both the horizontal and vertical displacements were restrained. According to in situ stress measurements of the 2-2 coal seam, the minimum principal stress was 5.5 MPa perpendicular to the direction of the P20314 face advance (Y-axis). The maximum principal stress was parallel to the retreating direction of P20314 face (X-axis) with a value of 6.0 MPa. The vertical stress was 4.25 MPa. A vertical stress of 2.1 MPa was applied on the top of the model to simulate the weight of the overlying strata.

In the model, the performance of the immediate floor and two coal seams were described using the strain-softening failure criterion, and the performance of other rocks was evaluated using the Mohr-Coulomb criterion.

The mechanical properties are listed in Table 2. The cohesion and friction angle of the two coal seams and the immediate floor degradation as the plastic shear strain increases, and these factors are assigned residual values when the plastic shear strain reaches 0.01. The residual value of rock or coal is mainly obtained by triaxial compression tests under different confining pressures.
In this paper, the null model was used to represent the performance of the longwall face goaf. First, the P20111, P20112, P20113, and P14102 longwall faces were excavated and calculated to equilibrium. Then, the P20314 tailgate, P20314 headgate, and P20313 headgate were excavated and calculated to equilibrium. The P20314 longwall face retreated along the X-axis with a larger advance of 50-100 m far away from the area of interest and a small advance of 5-10 m near the area of interest at each longwall retreat. During this process, the coal seam was removed from the model. In the software, cable elements were used to model the anchor cable and rockbolt performance, and the properties of the support elements are listed in Table 3.

The FLAC3D model and selected properties were calibrated via the P20313 headgate convergence at the #6 measuring station as the P20314 face retreated.

Figure 12 presents a comparison of the numerical results and field measurements for the P20313 headgate convergence at the #6 measuring station. As the P20314 face approached the #6 measuring station, the convergence of the P20313 headgate gradually increased. When the P20314 face was 30 m in front of the #6 measuring location, both the field measurements and numerical results showed that the convergence rapidly increased. The maximum convergence values were approximately the same. The numerical simulation predicted vertical and horizontal convergence of 2596 mm and 3045 mm, respectively. The above results were in good agreement with the field measurements, which showed a vertical convergence of 2577 mm and a horizontal convergence of 3012 mm. A large difference in the P20313 headgate convergence occurred, and this discrepancy may have been related to an inherent defect in the FLAC3D model, which cannot simulate the rock mass detachment or separation that occurs in the field. Another reason for this discrepancy was that rock masses in the field are heterogeneous, which was not considered in the FLAC3D model. However, the numerical results in this paper can well reflect the mechanical behavior of rock mass to a large extent.

### 3.2 Numerical results

#### 3.2.1 Numerical results at the #6 measuring station

As the P20314 face approached the #6 measuring station, the vertical stress at the center of chain pillar gradually increased,
as illustrated in Figure 12. When the P20314 face was 30 m in front of the #6 measuring station, the vertical stress reached its maximum value of 36.23 MPa and subsequently decreased rapidly. The convergence of the P20313 headgate remained the same until the P20314 working face was 30 m in front of the #6 measuring station. After the P20314 face had passed the #6 measuring station with a distance of 30 m, the horizontal convergence of the P20313 headgate increased linearly, thereby leading to gateroad failure. After the P20314 working face had passed the #6 measuring station with a distance of 45 m, the vertical convergence of the P20313 headgate increased quickly. Figure 13 shows the distribution of the failure zones and vertical stress near the #6 measuring station when the P20314 working face retreated to three positions relative to the #6 measuring station. These three positions corresponded to the three stages in Figure 7.

When the P20314 working face was 15 m behind the #6 measuring station, the concentrated vertical stress at the chain pillar had already appeared and two peaks occurred in the vertical stress curve. The peak values of the vertical stress were 28.7 and 29.9 MPa, and the peak value near the P20313 headgate was higher than the other value. Many plastic zones were observed around the P20313 headgate, and elastic zones with a width of 10 m remained in the middle of the chain pillar. However, the P20313 headgate and the chain pillar remained stable.

When the P20314 working face was 30 m in front of the #6 measuring station, the vertical stress concentration at the chain pillar increased. At this time, two peaks were observed in the vertical stress curve and the peak values increased to 42.4 and 40 MPa. The peak value near the P20314 tailgate was higher than the other value. At this time, the plastic zones around the P20313 headgate had increased significantly, and most of the zones at the chain pillar had failed. The additional loading from the roof had transferred to the chain pillar and the surrounding rock of the P20313 headgate.

When the P20314 working face was 75 m in front of the #6 measuring station, the vertical stress concentration at the

**TABLE 3** Properties of the support elements used in the model

| Property                              | Values          |
|---------------------------------------|-----------------|
| Rockbolt/Anchor cable                 |                 |
| Elastic modulus (GPa)                 | 200/200         |
| Tensile yield strength (kN)           | 390/1600        |
| Stiffness of the grout (N/m)          | 2e9             |
| Cohesive capacity of the grout (N/m)  | 4e5             |

**FIGURE 12** Deformation of the P20313 headgate and vertical stress in the chain pillar with P20314 face retreat (negative and positive numbers on the horizontal coordinate axis indicates that the P20314 face was behind and in front of the #6 measuring station, respectively)
chain pillar decreased; hence, the chain pillar was in the residual state. Two peaks remained in the vertical stress curve, and they were reduced to 22.5 and 30.7 MPa. At this time, the peak value near the P20313 headgate was higher than the other value. The failure zones around the P20313 headgate further increased, and the chain pillar was completely damaged.

3.2.2 | Induced stress distribution and failure zone distribution at the residual coal pillar in the upper coal seam

Figure 14 shows the distributions of the failure zone and the vertical stress in the area of interest of the 2-2 coal seam when the P20314 working face retreated to various positions.
relative to the #6 measuring station. The numbers in Figure 14(A) correspond to the position and value of the maximum vertical stress that occurred.

It is necessary to calculate the caved zone height of the P20314 face in order to obtain the damage condition of the S1 coal pillar. According to the theory of ground pressure,
“three zones” were formed after mining.28,29 The formula for the caved zone height is presented as formula (1).30

\[
\sum h = \frac{M}{K_p - 1}
\]  

(1)

where \(\sum h\) represent the thickness of the caved zone; \(M\) represents the thickness of the coal seam to be mined; and \(K_p\) represents the bulking factor of caved rock.

According to laboratory measurements, the bulking factor of mudstone is 1.25, which of the 2-2 coal seam is 1.2 and that of sandy mudstone is 1.3.

The sandy mudstone had an average thickness of 5 m and was located between the 2-2 and 2-2p coal seams. The height of the 2-2 coal seam was 3.5 m. After P20314 retreated from the area under the S1 coal pillar, the sandy mudstone (5 m) and 2-2 coal seam (3.5 m) formed the caved zone. P20314 mining inevitably caused part of the S1 coal pillar to collapse into blocks, and the remaining S1 coal pillar gradually reduced to an isolated right-triangular coal pillar as shown in Figure 14(A).

According to Figure 14(A), the position of the maximum vertical stress changed only slightly; hence, the loading from the overburden strata was continuously transferred to this area. In the region near the right angle of the right-triangular coal pillar, the vertical stress increased from 44.0 to 54.8 MPa and subsequently decreased to 48.9 MPa. When the P20314 face was 45 m in front of the #6 measuring station, the vertical stress in the triangle coal pillar reached its maximum value. As shown in Figure 14(B), the failure zones of the right-triangular coal pillar increased as the P20314 face retreated. When the P20314 face was 45 m in front of the #6 measuring station, the vertical stress at the chain pillar in the study area increased continuously and the value of the vertical stress increased as P20314 retreated through the study area. When P20314 was 30 m in front of the #6 measuring station, the chain pillar in the study area decreased and the vertical stress at the chain pillar reached the maximum value. When P20314 was more than 30 m in front of the #6 measuring station, the chain pillar in the study area was almost completely in a plastic state and its supporting capacity decreased, which resulted in the rapid and large deformation of the pillar side of the P20313 headgate.

According to Figure 14(A), as P20314 retreated, the vertical stress in the triangular area near the right angle in the 2-2 coal seam increased continuously and the value of the vertical stress increased from 38.6 to 52.8 MPa.

As shown in Figure 15(A), the loading on the whole chain pillar in the 2-2 coal seam increased initially and subsequently decreased. When P20314 was 30 m in front of the #6 measuring station, the vertical stress at the chain pillar reached the maximum value. Figure 15(B) shows that the failure zone of the chain pillar in the 2-2 coal seam increased continuously as P20314 retreated through the study area. When P20314 was 30 m in front of the #6 measuring station, the elastic zone of the chain pillar in the study area decreased and the vertical stress at the chain pillar reached the maximum value. When P20314 was more than 30 m in front of the #6 measuring station, the chain pillar in the study area was almost completely in a plastic state and its supporting capacity decreased, which resulted in the rapid and large deformation of the pillar side of the P20313 headgate.

As shown in Figure 15(A), as P20314 retreated, the vertical stress in the triangular area near the right angle in the 2-2 coal seam increased continuously and the value of the vertical stress increased from 38.6 to 52.8 MPa.

As shown in Figure 15(B), the solid rib of the P20313 headgate also exhibited the phenomenon of the elastic zone decreasing and the failure zone increasing. When P20314 was 30-45 m in front of the #6 measuring station, the failure zone of the coal body in the solid rib increased in a large area. When P20314 was 45-75 m in front of the #6 measuring station, the failure zone of the coal body in the solid rib increased to a lesser degree. When P20314 was more than 45 m in front of the #6 measuring station, a large and rapid deformation occurred in the solid rib of the P20313 headgate.

According to the above analysis, in the triangular area of the 2-2 coal seam, the chain pillar on one side of the P20313 headgate was initially in a strain-softening state and the coal body on the solid rib of the P20313 headgate was subsequently in a strain-softening state. The pillar rib of the P20313 headgate underwent a large and rapid deformation, and the solid rib subsequently appeared.
FIGURE 15  Comparison of the induced stress distributions (A) and failure zone distributions (B) at the study site in the lower coal seam with the P20314 face advanced to various positions relative to the #6 measuring station (negative numbers correspond to the #6 measuring station being in front of the P20314 face)

(A) The induced stress distribution in 2-2 coal seam

(B) The failure zone distribution in 2-2 coal seam
4 | FAILURE MECHANISM OF THE GATEROAD SYSTEM

To obtain the roof structure, the height of “three zones” must be calculated after the longwall face excavation. According to the theory of ground pressure, “three zones” were formed after mining as illustrated in Figure 16. The formula for the caved zone height is presented as formula (1). According to laboratory measurements, the bulking factor of mudstone is 1.25.

Formula (1) indicated that mudstone (9.8 m) formed the caved zone after the retreat of the longwall faces in the 2-2 coal seam. According to on-site monitoring, fine sandstone (18.2 m), medium sandstone (15.1 m), sandy mudstone (20.8 m), and mudstone (14 m) formed the fractured zone.

Based on the foregoing analysis, after P20314 retreated from the area that was under the S1 coal pillar, the sandy
mudstone (5.0 m) and 2-2 coal seam (3.5 m) formed the caved zone. According to on-site monitoring, mudstone (9.8 m), fine sandstone (18.2 m), medium sandstone (15.1 m), sandy mudstone (20.8 m), and mudstone (14 m) formed the fractured zone.

Based on the above analysis, fine sandstone (18.2 m), medium sandstone (15.1 m), sandy mudstone (20.8 m), and mudstone (14 m) were the common components of the fractured zones after mining in the upper and lower coal seams as illustrated in Figure 16.

When P20314 began to retreat, the longwall faces in the 2-2 coal seam had been excavated for more than one year and a stable roof structure formed over the goaf. After P20314 retreated from the area under the S1 coal pillar, part of the S1 coal pillar collapsed into blocks and the remaining S1 coal pillar gradually reduced to an isolated right-triangular coal pillar. At the same time, the overlying strata of the S1 coal pillar moved again, which resulted in large deformations of the chain pillar and surrounding rock of the P20313 headgate.

**Figure 17**  Formation of the triangular slab B of fine sandstone
According to the theory of ground pressure, the overburden strata over the goaf reached equilibrium after mining. The strata in the lower part of the fracture zone fractured into beams near the face end of the longwall face. One end of the rock beam fractured above the coal body and was supported by the coal body and the immediate roof, whereas the other end was supported by the caved stones in the goaf. A “fractured arch” was composed of positions at the end of each fractured strata in the fractured zone.

On-site monitoring of other longwall faces with similar geological conditions in the 2-2 coal seam showed that the position where the fine sandstone fractured in the fractured zone of the P20314 longwall face was directly above the chain pillar and the fractured position was 8 m away from the P20314 tailgate as illustrated in Figure 16. The fractured position of the fine sandstone in the fractured zone of the P20112 and P20113 longwall faces was 10 m away from the coal wall.

According to the above analysis, the P20314 longwall face retreated through the area of interest and formed a right-triangular coal pillar in the 2-2 coal seam as shown in Figures 16 and 17. The fine sandstone strata in the overburden strata of the triangular coal pillar were fractured to form “triangular slab B”. Other strata that belonged to the fractured zone and were above the fine sandstone also formed a triangular slab; however, their sizes were increasingly large. The above analysis demonstrated that “triangular slab B”, which was formed by the fine sandstone, bore the vertical stress that was caused by the excavation of the longwall faces in the two coal seams. At the same time, triangular slab B was supported by two coal seams and sandy mudstone.

In Figure 17, the position of D-D is sectioned to form the movement figure of the overburden strata as shown in Figure 16.

Figures 16(A) and 17(A) correspond to stage 1 of the failure process of the P20313 headgate. This failure mode occurred where the #6 measuring station was in front of the P20314 working face with a distance of 74–10 m. The P20313 headgate was located under the cantilever beam structure of the overburden strata. The gateroad was mainly affected by the lateral abutment pressure caused by the excavation of longwall faces in the 2-2 coal seam. At this time, the chain pillar in the 2-2 coal seam remained stable.

Figures 16(B) and 17(B) correspond to stage 2 of the failure process of the P20314 headgate. This failure mode occurred approximately where the #6 measuring station was 10 m in front of and 30 m behind the P20314 working face. At this stage, the fine sandstone above the S1 coal pillar formed the shape that is illustrated in Figure 17(B) and the overburden strata of the triangular coal pillar were fractured to form the structure that is shown in Figure 16(B). According to the above analysis, at this stage, many coal bodies in the two coal seams at the study site remained elastic and the triangular coal pillar in the upper coal seam remained stable overall. The compressive strength of the chain pillar in the lower coal seam was lower than that of the solid rib of headgate. When P20314 was 30 m in front of the #6 measuring station, under the huge loading of overburden strata, the overall loading of the chain pillar in the lower coal seam reached the maximum value and the chain pillar as a whole entered the state of strain-softening.

Figures 16(C) and 17(C) correspond to stage 3 of the failure process of the P20313 headgate. This failure mode occurred approximately where P20314 was 30 to 75 m in front of the #6 measuring station. As P20314 continued to retreat, “triangular slab B” eventually formed and the loading that it bore gradually reached the maximum value. When P20314 was 30–45 m in front of the #6 measuring station, the chain pillar on one side of the P20313 headgate was in the state of strain-softening. The decrease of the bearing capacity of the chain pillar caused “triangular slab B” to rotate and sink and the failure zone of the solid rib of the P20313 headgate increased substantially. When P20314 was more than 45 m in front of the #6 measuring station, the triangular coal pillar in the upper coal seam fully entered the state of strain-softening under the action of gravity of the overburden strata and the solid rib of the P20313 headgate in the lower coal seam was in the plastic state in a large area, which resulted in triangular slab B’s integral subsidence. In the upper part of the chain pillar in the lower coal seam, the subsidence of the triangular slab B was the most severe. The rotation and subsidence of triangular slab B reduced the loading on the chain pillar and increased the loading on the solid rib of the P20313 headgate, which is demonstrated by the increasing vertical stress near the right corner of the triangular area in Figure 15(A). Due to the rotation and subsidence of triangular slab B, many coal bodies were extruded on the pillar rib of the P20313 headgate and the outburst of the solid rib was severe as shown in Figure 7.

According to the above analysis, at the study site, the distance between the 2-2 coal seam and the 2-2 coal seam was only 5 m. Due to the false layout of the longwall system, triangular slab B above the triangular coal pillar appeared after mining in two coal seams. The huge loading from the overburden strata concentrated on “triangular slab B” and was transmitted downward to the 2-2 coal seam, which eventually led to the failure of the chain pillar and the P20313 headgate in the area of interest.

When designing longwall system layouts in close-distance coal seams, whether isolated coal pillars remain in the upper coal seam after mining should be determined and lower coal seam roadways should not be located under such seams.

## 5 | DISCUSSION

Because part of the P20313 headgate had failed, to ensure that the P20313 longwall face could retreat successfully, the P20313 ancillary headgate was set up on the side of the area of interest where the P20313 headgate was destroyed.
The area under the triangular slab B was in the range of high vertical stress concentration. Severe roof movements have occurred in this area, and the 2–2 coal seam had been crushed into blocks and was in the residual state. Considering that the range of the broken coal body in the 2–2 coal seam was large, to ensure the safety of the P20313 auxiliary headgate, the gateroad should not be arranged in the lower part of the residual right-triangular coal pillar in the 2–2 coal seam. As illustrated in Figure 18, the stagger distance between the P20313 auxiliary headgate and P20313 headgate should be more than 33 m and the length of the P20313 auxiliary headgate should be more than 82 m.

The P20313 auxiliary headgate was designed and three schemes were proposed as illustrated in Figure 18. To ensure the appropriate ventilation, transportation and safety of the gateroad, the size and anchor-mesh-cable support of the P20313 auxiliary headgate were equivalent for the P20313 headgate.

In the first scheme, which is illustrated in Figure 18(A), the distance between the P20313 auxiliary headgate and the P20313 headgate was only 14 m. According to the above analysis, part of the P20313 auxiliary headgate was under triangular slab B. Drivage in this area is not conducive to gateroad support. Therefore, the first scheme is excluded.
As illustrated in Figure 18(B), the distance between the P20313 auxiliary headgate and the P20313 headgate was 75 m. In the second scheme, most of the P20313 auxiliary headgate was located under the goaf of the 2-2\textsubscript{L} coal seam. Because the area under the goaf of the 2-2\textsubscript{L} coal seam was gradually restored to the initial stress,\textsuperscript{39} maintaining the gateroad in this area was easy and strengthening the gateroad support can ensure the normal operation of the gateroad when P20313 retreated. However, part of the gateroad was vertical with respect to the P20313 headgate and located under the chain pillar in the 2-2\textsubscript{L} coal seam (width of the chain pillar in the 2-2\textsubscript{L} coal seam was 20 m). According to the above numerical simulation, the gateroad in this area was affected by the vertical stress concentration induced by the chain pillar in the 2-2\textsubscript{L} coal seam. The average vertical stress of this area was 15 MPa. According to mining experience, strengthening the gateroad support can ensure the normal operation of the gateroad.\textsuperscript{40} When the P20313 face retreated, the working face initially shrank and subsequently enlarged. Furthermore, the coal production of the second scheme is smaller than that of the third scheme.

As illustrated in Figure 18(C), the distance between the P20313 auxiliary headgate and the P20313 headgate was 44 m. In the third scheme, most of the P20313 auxiliary headgate was located under the goaf of the 2-2\textsubscript{L} coal seam. Part of the gateroad was located under the chain pillar in the 2-2\textsubscript{L} coal seam and oriented parallel to the P20313 headgate. As the P20313 retreated, the gateroad was influenced by the concentrated stress induced by the chain pillar in the 2-2\textsubscript{L} coal seam and the abutment stress of the P20313 face. Mining experience of longwall faces with similar conditions in the 2-2 coal seam indicates that the safety of the gateroad can be ensured by strengthening the support of the gateroad and the advance timbering of the P20313 face.

Based on the above analysis, the third scheme was finally selected and applied in the field. The support of the P20313 auxiliary headgate under the chain pillar in the 2-2\textsubscript{L} coal seam was strengthened. A U-shaped steel shed and hydraulic prop were used to reinforce the support of the gateroad in this area. The type of U-shaped steel was 25U, and it had a row spacing of 1000 mm. The type of hydraulic prop was DW35-350/110X, and there were four hydraulic props in each row, with a row spacing of 1000 mm. When the P20313 face retreated, the maximum horizontal convergence and vertical convergence of the P20313 auxiliary headgate were 0.5 and 0.3 m, respectively, and the surface of the gateroad was approximately intact, thereby ensuring the safe retreat of the P20313 working face.

6 | CONCLUSIONS

1. After the longwall face in the lower coal seam retreated through the area under the irregular coal pillar in the upper close-distance coal seam, the bearing area of the residual coal pillar decreased and the roof pressure continuously concentrated at the residual coal pillar. Isolated triangular slab rock was formed above the triangular residual coal pillar, and the weight of overlying strata was transferred downward through the triangular slab rock.

2. When the chain pillar in the lower part of the residual coal pillar was destroyed due to loading that exceeded its carrying capacity, the upper triangular slab rock rotated and sank, which resulted in the intensification of the concentrated stress in the solid rib of the gateroad in the lower coal seam.

3. The analyses performed here suggested that in the design of the longwall system, lower coal seam roadways under an isolated residual coal pillar in the upper coal seam should be avoided when mining in close-distance coal seams.

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ORCID

Hefu Shang https://orcid.org/0000-0002-2537-3562
Shanchao Hu https://orcid.org/0000-0003-0457-7184

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