INTRODUCTION

The formation of coal seams is affected by various factors, such as geological structure, invasion, and surface subsidence. Therefore, coal seams exist in a variety of geological conditions. With the increasing intensity of coal mining, coal seams with favorable geological structure and shallow depths are diminishing continuously. In recent years, miners have had to overcome the challenge of coal extraction from close-distance coal seams at many mining regions. A number of studies have already been performed to resolve the issues encountered during the mining of close-distance coal seams. In these studies, the thickness of strata between close-distance coal seams is over 8 m. The numerical calculation is a commonly used method to study the stress distribution law and rock movement in close-distance coal seams (Table 1).

Close-distance coal seams are often extracted following a downward mining sequence, during which the mining of the overlying coal seam is almost the same as mining of a single coal seam. However, the mining process of the underlying coal seam is affected by mining activity in the overlying coal seam. In this case, the roof structural integrity of the underlying coal seam is lost and it leads to movements of overlying stratum over the underlying mining roadway. These movements eventually cause technical, economic, social, and environmental hazards to...
natural structures on the underlying mining roadway and surface. At the same time, because the structure of the overlying stratum remains unstable after mining the coal pillars in the remaining region of the overlying coal seam and the upper coal seam, the roof of the underlying coal seam and the interior of the coal body are affected by a complex stress field. This results in significant strata pressure behavior in the underlying mining roadway, in addition to continuous and intense deformation of the roadway. Therefore, a proper roadway layout and supporting system are critical for conducting mining activity in close-distance coal seams.

The 3\text{upper} coal seam (UCS) and 3\text{lower} coal seam (LCS) are being extracted in the Fucun Coal Mine. The average spacing between these two coal seams is only 6 m, which are considered as ultraclose coal seams. The mining at Fucun Coal Mine takes a different approach to that at other coal mines. Specifically, after the mining process at one longwall face in the UCS is completed (after approximately 6 months), the LR will then be excavated from the goaf region of the UCS in the downward direction. The mining of the UCS has caused different levels of damages to the roof of the LR and the LR becomes unusable. This phenomenon occurred at the same time as mining activity on an adjacent

![Figure 1](image-url)
longwall face in UCS. In this paper, a physical model experiment and a 3D numerical calculation were performed based on the geological conditions of contiguous coal seam mining in Fucun Coal Mine. The characteristics of the overlying strata’s movement and the stress distribution of UCS was study. According to the results of the study, a proper layout of the mining roadway as well as stability control technology for the surrounding rock in the 1007 haulage roadway at the LCS was proposed.

2 | LABORATORY TESTING AND FIELD MEASUREMENTS

2.1 | Overview of geological conditions

The Fucun Coal Mine is located in Zaozhuang, Shandong, China (Figure 1A). Both the 3_upper and LCSs belong to the Shanxi Formation and are buried at an average depth of 500 m. The UCS is a medium-hard coal seam with a thickness ranging from 5.35 to 5.77 m (average 5.5 m), an average inclination angle of 7°, and f = 1.5 to 2.2. The immediate roof and main roof of the UCS are 0.3 m thick mudstone and 5 m thick siltstone, respectively. The LCS is a medium-hard coal seam with a thickness ranging from 4.03 to 4.46 m (average 4.20 m) and f = 1.5 to 2.2. The immediate base of the LCS is 0.78 m thick sandstone. The intermediate stratum between the 3_upper and LCSs has an average thickness of 6 m and consists primarily of siltstone, mudstone, and sandy mudstone. Extracting coal from the UCS and LCS is considered as mining from close-distance coal seams. After the mining process at longwall face 1001 in the UCS is completed after 7 months, material roadway 1001 in the LCS will be excavated from the goaf region at longwall face 1001 in the UCS at the same time as the mining process at longwall face 1007 in the UCS. The mine location and panel layout will be performed following the sequence shown in Figure 1, where steps 1 to 5 represent the construction sequence and \( L_i \) is the distance between haulage roadway 1007 and upper haulage roadway 1008. The columnar rock formation in the Fucun Coal Mine is shown in Figure 2.

2.2 | Laboratory testing

Testing samples were collected from the LCS and its roof and floor. The compressive, tensile, and shear strengths of these rock samples were measured using an electronic universal testing machine, as shown in Figure 3. The testing results and other required initial properties of rock masses are shown in Table 2.

| Column | Lithology     | Thickness (m) | f   | Remark         |
|--------|---------------|---------------|-----|----------------|
| Mudstone | 21.60         | 4-6           |     |                |
| Sanstone | 26.30         | 6-8           |     | Overlying strata|
| No. 2 coal seam | 0.20         | 1.5-2.2      |     |                |
| Sandy mudstone | 2.71       | 4-6           |     |                |
| Medium sandstone | 1.85       | 6-8           |     |                |
| Fine sandstone | 9.10        | 6-8           |     |                |
| Medium sandstone | 10.00      | 6-8           | Main roof |
| Siltstone | 5.10         | 4-6           |     | Immediate roof |
| Mudstone | 0.30          | 4-6           |     |                |
| 3_upper coal seam | 5.50     | 1.5-2.2      | Coal |
| Mudstone | 0.30          | 4-6           |     |                |
| Siltstone | 5.55         | 4-6           | Interlayer strata |
| Sandy mudstone | 0.15       | 6-8           |     |                |
| 3_upper coal seam | 4.20     | 4-6           | Coal |
| Mudstone | 0.78          | 4-6           | Immediate floor |
| Siltstone | 9.0          | 6-8           | Main floor |
| Sandy mudstone | 6.02       | 4-6           | Underlying strata |

FIGURE 2 Columnar rock formation in the Fucun Coal Mine

2.3 | Field measurements

Material roadway 1001 in the LCS is arranged with an internal staggered layout with a misalignment of 60 m beneath the goaf region of longwall face 1001 in the UCS. Material roadway 1001 in the LCS is excavated at the same time as the mining activity at longwall face 1007 in the UCS. With continuous mining at longwall face 1007 in the UCS, the strata pressure behavior at material roadway 1001 in the LCS becomes increasingly significant, accompanied by severe surface destruction of the surrounding rock around the roadway and fracturing of anchor rods at certain local regions. As shown by the borehole televiever (Figure 4A), the surrounding rock has developed fissures and fractured slightly. Part of the surrounding rock is already detached from the adjacent region. Near the two sides, the strong deformation of the surrounding rock caused the borehole to be blocked during the borehole monitoring process. Several monitoring stations were deployed in the middle
section of the roadway to measure the deformation of the surrounding rock. The measurement results in Figure 4B show that the maximum displacement of the roof and floors is 210 mm and the maximum displacement of the side is 293 mm. Material roadway 1001 in the LCS has already undergone several major reworks during its service period. The on-site monitoring results indicate that the layout of the roadway and the control of the surrounding rock are improperly set up. Haulage roadway 1007 in the LCS will be excavated at the same time as the mining activity at longwall face 1008 in the UCS after completing the mining process at longwall face 1007 in the UCS. Hence, the layout of the roadway and methods to control the deformation of the surrounding rock must be designed properly to prevent similar deformation and destruction occurring in haulage roadway 1007 in the LCS.

3 | PHYSICAL MODELING OF ROOF MOVEMENT

Mining activity at the longwall face will cause different types and different levels of supporting pressure bands to form in neighboring locations. Among these supporting pressure bands, the ones in the oblique upper portion of the longwall face generally have a small influencing zone within the range of 15-30 m. Under rare conditions, the influencing zone could reach 35-40 m. After the mining process at longwall face 1001 in the UCS was completed after 7 months, material roadway 1001 in the LCS was then excavated with an internal staggered layout with a misalignment of 60 m beneath the goaf region of longwall face 1001 in the UCS. At the same time, the mining activity at longwall face 1007 in the UCS also began. As the mining activity progressed at longwall face 1007 in the UCS, strong strata pressure behavior occurred at material roadway 1001 in the LCS, accompanied by significant deformation features.

3.1 | Characteristics of the movement at the UCS main roof

Mining activity at a single longwall face in the UCS will cause destruction of the old roof stratum following a vertical “O-X” pattern, after which a “masonry beam” structure will form in the overlying stratum.26-31 As demonstrated by a considerable number of studies,31-37 the mining activities at multiple longwall faces will enlarge the fracture zone of the overlying stratum when the coal seam is deeply buried. In this case, the key layers located in the upper middle part of the fracture zone far away from the coal seam may experience rotation or fracturing and become unstable. These phenomena have a substantial impact on strata pressure at the mining site.38,39

As shown in Figure 5, the key layers at a lower elevation (KYLE) experience “vertical O-X” fracturing and form a load-bearing structure of “masonry beam + cantilever beam” after mining activity at a single longwall face. This feature represents the first movement of the overlying stratum. After mining activities have been conducted at multiple longwall faces, the key layers at higher elevations far away from the longwall face are destroyed and become unstable. These layers experience “horizontal O-X” fracturing and form “triangular plate” structures, which affect the strata pressure behavior. This phenomenon represents the second movement of the overlying stratum.

As shown in Figure 6A, B, the energy released and stress transmitted during the destruction of key layers at a high elevation (KYHE) as they become stable will easily cause strata pressure behavior at the longwall face. Meanwhile, mining activities at multiple longwall faces will create a laterally larger goaf region. In this case, the movement of the KYHE will affect the strata pressure at the mining site differently compared with the case of mining at a single longwall face. As shown in Figure 6B, the key layers of the overlying stratum far away from the longwall face in the UCS will experience “O-X” fracturing under certain conditions. These layers will become unstable, fractured, and rotated during mining activity at longwall face 1007 in the UCS. The impact of the rotation will be directly affected in the region above the goaf area of longwall face 1001 in the UCS. In other words, the stress above the goaf area will be transferred to the mining roadway in the LCS through the interlayer layers and cause strong strata pressure behavior in the mining roadway. In addition, the strata pressure behavior at material roadway 1001 in the LCS becomes more intense as longwall face 1007 in the UCS becomes closer to a square. Therefore, it is inferred that the mining process of the adjacent longwall face and the expansion of the goaf will cause the key layer of the overlying stratum...
strata far from the coal seam above the UCS to move, fracture, and become unstable. The second movement of the overlying stratum causes the overlying load to be applied to the base rock layer in the goaf, which results in severe strata pressure behavior in the mining roadway in the LCS.

### 3.2 Physical similarity simulation

#### 3.2.1 Physical model

There are various examples of physical modeling of mining-induced ground movements in the literature. In this study, a scaled physical model was designed and simplified based on the geological and engineering conditions of the No.3 coal seam in Fucun Coal Mine. The physical model was built in accordance with the principles of similarity theory. The dimensions of the model, strength and density of the material in the physical model should satisfy the fundamental condition of the similarity theory: \[ \frac{C_o}{C_p \times C_L} = 1, \quad C_t = \sqrt{C_L} \] (1)

where \( C_o = \sigma_o / \sigma_m, C_p = \rho_p / \rho_m, C_L = L_p / L_m \)

In the above equations, \( C_o \) is the constant of stress similarity, \( C_p \) is the constant of density similarity, \( C_t \) is the constant of similarity geometry, and \( C_L \) is the similarity constant for time; the subscript \( P \) stands for the prototype based on field conditions while \( m \) stands for the physical model.

As shown in Figure 7, the physical similarity simulation was designed based on the principle of similarity. The test was performed by considering the effective dimension of the model as well as the condition of the roof/floors in the coal seam. In the experiment, the geometric similarity ratio, stress similarity ratio, cylinder pressure supply, volumetric weight similarity ratio, and time similarity ratio were set as 100, 150, 0.067 MPa, 1.5, and 10, respectively. The dimension of the model was 5.0 × 1.36 × 0.3 m (length × height × thickness). According to the actual temporal and spatial relationship in the mining area, the left 121 cm of the model is considered as longwall face 1007 in the UCS, the middle 250 cm as longwall face 1001 in the UCS, and the right 121 cm as working surface 1002 in the UCS. The coal pillar between each neighboring longwall face is 4 cm high. Longwall face 1002 in the UCS was already depleted before mining at longwall face 1001 in the UCS. Considering the similarity in the physical and mechanical properties between prototype stratum and the material used in the model, we selected river sand and mica as the aggregates and gypsum and lime as the cementing

| Lithology         | Compressive strength (MPa) | Tensile strength (MPa) | Elasticity modulus (GPa) | Poisson ratio | Density (kg/m³) | Cohesion (MPa) | Friction angle (°) |
|-------------------|-----------------------------|------------------------|--------------------------|---------------|-----------------|-----------------|-------------------|
| Fine sandstone    | 89.81                       | 15.12                  | 17.37                    | 0.16          | 2600            | 4.3             | 42                |
| Sandy mudstone    | 32.62                       | 1.89                   | 12.64                    | 0.26          | 2630            | 2.5             | 30                |
| UCS               | 9.42                        | 0.73                   | 3.67                     | 0.31          | 1500            | 1.1             | 20                |
| Mudstone          | 11.96                       | 1.43                   | 9.90                     | 0.25          | 2520            | 2.2             | 27                |
| Fine sandstone    | 91.38                       | 11.96                  | 16.45                    | 0.16          | 2600            | 4.1             | 40                |
FIGURE 4  A. Borehole television observation; (B) Condition of the material roadway 1001 in the LCS

FIGURE 5  Predictive 3D model of overlying strata structure
FIGURE 6  Model of the movement at the UCS overlying stratum. A, Plan; (B) Profile

FIGURE 7  Physical similarity simulation experiment. A, Physical model; (B) Layout of the model
materials in this study. Sine gypsum tends to condense and harden quickly; hence, a retarder (1% borax aqueous solution) was added to delay the condensation and hardening.

### 3.2.2 Analysis of tests results

According to actual production conditions, it takes approximately 1.7 hours for the coal cutter to perform one cutting. Based on the principle of similarity, the extraction step and time were set as 7.5 mm and 10 minutes, respectively. The roadway was excavated by approximately 10 m per day. Based on the principle of similarity, the excavation step and time were set as 100 mm and 30 minutes, respectively. In the similarity simulation test, longwall faces 1002, 1001, and 1007 in the UCS were excavated separately. Part of the excavation process and results of the similarity model are shown in Figure 8.

Upon completing the excavation in the model, the total height of the fallen zone and the fracturing zone was approximately 95 m, where the fallen zone was approximately 29 m high and the fracturing zone was approximately 66 m high. In addition, longitudinal cracks formed in the middle section of the KYHE during excavation at longwall face 1001 in the UCS. These cracks kept expanding with increasing excavation space. When excavation started at longwall face 1007 in the UCS, the KYHE continued moving downward and became rotated, fractured, and unstable. Therefore, the mining process in the UCS has a certain impact on the migration of key layers far away from the coal seam. Moreover, the movement, rotation, and fracturing of the KYHE will in turn affect the base rock plate at the mining site and result in strong strata pressure behavior in the mining roadway. Because material roadway 1001 in the LCS is located within the influencing zone of the rotation and fracture behavior of the overlying stratum, stress concentration will easily occur in the roadway and cause it to deform severely. These findings indicate that the layout and location of the mining roadway in the LCS is designed improperly under the current geological conditions.

### 4 NUMERICAL MODELING OF STRESS DISTRIBUTION IN THE FLOOR

During the mining process of close-distance coal seams, the stability of the underlying mining roadway after coal extraction is dependent on both the strength and integrity of the surrounding rock and the stress environment of the surrounding rock. The stress in the surrounding rock near the longwall face will be redistributed with the mining process at the coal seam. At the same time, changes in stress (such as concentration and unloading) will be transmitted toward deeper locations in the base stratum and result in a change of the stress field in the floor of the roadway. The rock body will be damaged when the bearing pressure reaches or exceeds the limit that the base rock layer can withstand. The mining activities at multiple longwall faces in the UCS of Fucun Coal Mine will cause the KYHE to fracture, rotate, and sink. The second movement of the overlying stratum will result in stress concentration at the roof plate of the LCS and strong strata pressure behavior at the mining roadway in the lower coal seam. To prevent stress concentration in the underlying mining roadway, the temporal and spatial evolution of stress at the floor of the UCS was explored during the mining process by FLAC3D numerical analysis.

#### 4.1 Numerical model and parameters

As shown in Figure 9, the dimensions of the numerical model were set as length \((x) \times \) width \((y) \times \) height \((z) = 800 \times 500 \times 102\) m. The strike and dip of the longwall face follow the length and width directions, respectively. The model consisted of 467 500-unit cells and 493 688 nodes in total. To eliminate the boundary effect, a 50 m wide space was set as the boundary region along the boundary faces of the model. A horizontal constraint was imposed on the left and right boundaries, horizontal and vertical constraints were imposed on the bottom boundary, and no constraint was imposed on the top boundary of the model. The
average buried depth of the UCS is approximately 510 m. A uniform load was applied in the model with respect to the buried depth. The average density of the rock layer was set as 2500 kg/m³. The lateral pressure coefficient was set as 1.03. A large deformation model was selected in the simulation. The Mohr-Coulomb constitutive model was used in our calculations. The physical and mechanical parameters of the coal seam and the stratum at the roof/floor were set as 0.58 times the original values measured from the laboratory test.\textsuperscript{49}

4.2 Analysis of numerical calculation results

4.2.1 Stress distribution at the mining floor of longwall face 1001 in the UCS

Figure 10 shows the stress distribution at the floor after mining activity at longwall face 1001 in the UCS. A stress measurement line A-A is plotted along the center of the longwall face in the UCS. The coordinates of each end of the stress line are (0, 250) and (800, 250).

As shown in Figure 10A, after the mining activity at longwall face 1001 in the UCS, the influencing zone of lateral supporting pressure along the coal wall and the stress concentration coefficient were approximately 80 m and 1.3-2.0, respectively. Figure 10B shows that the stress at the floor of the goaf region follows a “W” shaped distribution, that is, “decreases-increases-decreases-increases” from left to right. The region within 65 m of the left coal wall in the longwall face is covered under the stress-decreasing zone where the stress is <5/6 of the original rock stress. This feature explains why material roadway 1001 in the LCS experienced a gentle pressure and small surrounding rock deformation before the mining activity started at longwall face.
1007 in the UCS. The stress was minimized and <0.2 MPa within 10-30 m of the left coal wall. A stress concentration behavior with a stress concentration coefficient of 2 was also observed at the section touching the base floor in the top plate in the middle of the goaf.

4.2.2 | Stress distribution at the floor of longwall face 1007 in the UCS

The mining process at longwall face 1007 in the UCS was conducted according to the distributed mining method, where each

FIGURE 11 The stress distribution at the floor in the mining process of working face 1007. (A) Working face advancing 230 m; (B) Working face advancing 400 m
mining step excavates 40 m. A-A, B-B, and C-C represent the vertical stress measurement lines in the rock layer at the floor. The measurement lines B-B and C-C are 30 m away from pillar. As shown in Figure 11A, the overlying KYHE above the UCS undergo displacement as the mining activity proceeds at longwall face 1007 in the UCS. The residual supporting pressure along the inclined direction of the longwall face 1007 in UCS is superimposed with the supporting pressure at the goaf region of longwall face 1001 in UCS. At the same time, the vertical stress on the bottom plate at locations near longwall face 1007 in the UCS starts to increase gradually and eventually forms a stress concentrated zone. In particular, the stress concentration coefficient is maximized and reaches 1.4-2.4 at 35-75 m from the coal pillar. Therefore, material roadway 1001

FIGURE 12 The stress distribution at the floor in the mining process of working face 1008. A, Working face advancing 230 m; (B) Working face advancing 400 m
in the LCS directly under this area will be affected substantially by the concentrated stress. This is the direct cause of the strong strata pressure behavior observed in this roadway. As shown in Figure 11B, the region within 11 m of the coal pillar is covered under the stress-decreasing zone where the stress is approximately 1/5-3/5 of the original rock stress. The magnitude of stress approaches that of the original rock stress at approximately 24 m from the coal pillar, and the local stress concentration coefficient is <1.2. Therefore, based on the distribution pattern of the bearing pressure and the width of the roadway, the location of material roadway 1001 in the UCS should be within 20 m of the coal pillar.

4.2.3 | Stress distribution at the mining floor of longwall face 1008 in the UCS

Figure 12 shows the distribution pattern of stress at the mining floor of longwall face 1008 in the UCS during the mining process. The influencing zone of the leading bearing pressure is approximately 70 m ahead of the longwall face (Figure 12A). The leading support pressure at the side of the coal pillar is superimposed with the lateral bearing pressure stress at longwall face 1007 in the UCS. The stress concentration coefficient is approximately 1.8-2.5 within this area. As the mining activity proceeds on longwall face 1008 in the UCS, the vertical stress on the floor near the side of the coal body in the front section of material roadway 1008 in the UCS begins to increase gradually and forms a stress concentrated zone with a stress concentration coefficient of 1.5-2.7. Therefore, a mining roadway in the LCS designed directly under this area would be subjected to strong stress interference, which would make it difficult to maintain the roadway. In other words, haulage roadway 1007 in the LCS should be designed within 19 m of the coal pillar. Combining our results with findings from the literature and the geological conditions on-site, the haulage roadway 1007 in the LCS should be designed following an internal staggered layout was suggested. In other words, haulage roadway 1007 in the LCS should be excavated beneath the goaf region of longwall face 1007 in the UCS and be 15 m (Figure 13) away from haulage roadway 1008 in the UCS in the horizontal direction.

5 | DISCUSSION AND APPLICATION

5.1 | Proper location of roadway in the LCS

According to the numerical results for stress evolution in the rock layer at the floor calculated during the mining process at the longwall face in the UCS, particularly focusing on the distribution pattern of the bearing pressure, the haulage roadway 1007 in LCS should be designed within 19 m of the coal pillar. Combining our results with findings from the literature and the geological conditions on-site, the haulage roadway 1007 in the LCS should be designed following an internal staggered layout was suggested. In other words, haulage roadway 1007 in the LCS should be excavated beneath the goaf region of longwall face 1007 in the UCS and be 15 m (Figure 13) away from haulage roadway 1008 in the UCS in the horizontal direction.

According to the stress evolution pattern in the plate during the mining process of the longwall face in UCS, the mining roadway in the lower coal seam should be designed in a low-stress zone. However, the stability of the mining roadway in the LCS is still worse than that in a single coal seam. Based on the results of field measurements in LR with unstable surrounding rocks, it is important to improve the stress characteristics of the anchor rods as well as the strength and stiffness of the supporting system. Such improvements can be achieved by increasing the diameter, length, and prestress of the anchor rod or adding supporting units to the anchor rod. By assigning sufficient initial prestress and reasonable supporting strength to the anchor rod, the surrounding rock will be provided with strong support from the beginning. This practice can prevent the surrounding rock from breaking loose and deforming during the initial stage. The criteria for adjusting the overall bearing capacity of the surrounding rock and establishing a supporting system for the coal roadway with a focus on high performance are as follows:

**FIGURE 13** The proper location of haulage roadway 1007 in the LCS
(a) high-performance supporting units: high-performance anchor rod set, steel strips, or surface supporting units with steel and mesh; (b) high anchoring performance: a proper “diastyle match”, extended or full-length anchoring; and (c) anchor rod (cable) combination support: proper match between the anchor rod and anchor cable to ensure overall high performance of the supporting system.

5.2 | Supporting system and application

Based on the supporting criteria for the mining roadway in the LCS, left-handed thread steel anchor rods with diameters of 20 mm and lengths of 2200 mm were used on the roof plate. The spacing between the anchor rods was 800 × 800 mm. At the same time, anchor cables with diameters of 22 mm and lengths of 5000 mm were also used to support the roof plate. The anchor cable consisted of 1 × 19 threads. These cables were arranged with a spacing of 2400 × 1600 mm. The lag of the anchor cable support is less than the total distance across 5 rows of anchor rods. Left-handed thread steel anchor rods with diameters of 20 mm and lengths of 2200 mm were used on the two sides of the roadway. The spacing between these anchor rods was 800 × 800 mm. At the same time, anchor cables with diameters of 22 mm and lengths of 4300 mm were also used to support the two sides. The anchor cable consisted of 1 × 19 threads. These cables were arranged with a spacing of 3200 × 1600 mm. All anchor rods were prestressed with a torque > 300 N/m. The tensions of the anchor cables on the roof plate and two sides were 220 and 150 kN, respectively. The angle between the top corner anchor rod and the roof plate was 15°. The angle between the bottom corner anchor...
rod and the two sides was also 15°. Figure 14 shows the supporting system of the roadway.

The surface displacement of the roadway is an important indicator for assessing its reasonable location and supporting effect. To validate the supporting performance on the roadway, several measurement stations were arranged in the haulage roadway 1007 in LCS. The surface displacement recorded from a typical measurement station is shown in Figure 15. The roadway was essentially stabilized after 1 month of observations. The cumulative displacement of the roof-to-floor was 138 mm and the cumulative displacement of the rib-to-rib was 102 mm. So far, haulage roadway 1007 in the LCS is relatively stable in general, which satisfies the production demand.

6 | CONCLUSION

A case study on the mining of close-distance coal seams (the UCS and LCS) in the Fucun Coal Mine was performed. Specifically, by combining a physical similarity simulation experiment and numerical calculation, the movement of the underlying stratum in the UCS, the temporal and spatial evolution of stress in the floor stratum in the UCS was investigated. The following conclusions were obtained:

The results of physical similarity simulation show that mining activities at multiple longwall faces in the UCS will expand the goaf region and cause the KYHE to rotate, fracture, and become unstable. These phenomena will result in redistribution of stress. Material roadway 1001 in the LCS is located within the rotation and fracture influencing zone of the KYHE. Therefore, material roadway 1001 in the LCS is affected substantially by dynamic pressure and exhibits strong strata pressure behavior. These findings indicate the reasons of large deformation in LR and the location of LR is improper under the current geological conditions.

Numerical calculations were performed to investigate the temporal and spatial evolution of stress in the rock layer at the floor during the mining process at each longwall face in the UCS. The results showed the LR’s location is not farther away from the coal pillar in the UCS, the better, but in a suitable location. Based on the distribution pattern of the bearing pressure, an internal staggered layout of haulage roadway 1007 in the LCS was finalized: the horizontal distance to the remaining coal pillar in the overlying coal seam is 11 m, and the distance to haulage roadway 1008 in the UCS is 15 m. Furthermore, based on the causes of instability in the mining roadway of the underlying coal seam and other existing problems, a support plan for the mining roadway in the underlying coal seam was proposed and the technical supporting parameters to stabilize the underlying mining roadway were determined. The numerical calculation and field application results demonstrated that the proposed plan can control the large-scale deformation of the LR’s surrounding rock effectively.

ACKNOWLEDGMENTS

The authors gratefully thank the anonymous reviewers for their constructive comments for improving the presentation. This research was supported by the Fundamental Research Funds for the Central Universities (2018XKQYMS10). All authors have agreed to the listing of authors. The authors thank Fucun Coal Mine for their support during the field test.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ORCID

Liu Zhu https://orcid.org/0000-0001-5122-212X
Qiangling Yao https://orcid.org/0000-0001-9900-4615
Xuehua Li https://orcid.org/0000-0001-9420-8635

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**How to cite this article:** Zhu L, Yao Q, Xia Z, Wang W, Li X. Study on the movement characteristics of the overlying stratum and surrounding rock control in ultraclose coal seams: A case study. *Energy Sci Eng*. 2020;8:1231-1246. [https://doi.org/10.1002/ese3.581](https://doi.org/10.1002/ese3.581)