Modeling study on the influence of the strip filling mining sequence on mining-induced failure

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Abstract
The strip filling mining method can solve the problems related to mining under structures, under aquifers, and under infrastructure (3U coal seams), while the reasonable selection of the mining and filling sequence still requires further investigation. The current study was conducted to investigate the stress and surface subsidence of a filling body (or coal pillar) under two filling sequences through theoretical analysis, similar simulation tests, and numerical simulations. To achieve optimal filling materials for the Liudong Coal Mine, a low-strength similar paste filling material composed of fly ash, gypsum, and sand was developed. The relationships between the strength and the cement ratio and between the strength and the sand-binder ratio were discussed. Similar simulation tests showed that mining scheme 1 (mining before filling) could lead to the formation of an isolated island coal pillar in the mining process, mining scheme 2 (filling before mining) had less influence on surface subsidence, and the stress on the filling body was smaller for scheme 2 than for scheme 1. The distributions of the stress and plastic zone in the two different mining and filling sequences were obtained through numerical simulations. The method of first filling and then mining could greatly reduce the stress concentration and plastic zone during the mining process. In summary, mining scheme 2 (filling before mining) can avoid the formation of isolated island coal pillars in the process of mining, and without considering other factors, scheme 2 should be adopted as much as possible.

KEYWORDS
3U coal seam mining, mining and filling sequence, proportioning experiment, surface subsidence
1 | INTRODUCTION

Coal resources are the main energy source in China, but the mining of coal in China, especially in the central and eastern parts of China, is facing problems related to mining under structures, under aquifers, and under infrastructure (3U coal seams).1-4 In recent years, the recovery of 3U coal seams has become a major challenge for the sustainable development of the coal mining industry in China. At present, there are approximately 13.79 billion tons of coal resources buried underground in large state-owned coal mines. In general, these trapped resources account for 10%-40% of minable coal resources. In some coal mines, this ratio has reached 100%.5-8

The preliminary coal mining method, in which villages are moved, is often used for mining, and the coal recovery rate can be guaranteed. However, the cost of moving villages is too high, villages occupy a large amount of land, and new residence choices are limited. Therefore, this method has been gradually eliminated. The mining of 3U coal seams without the relocation of villages can be realized by using the filling mining method. The essence is to replace coal resources with filling materials and thus control surface subsidence.9 In the eastern plain area of China, the filling mining method has been widely used in mining areas where there is a large distribution density of villages due to the shortage of minable coal resources.10-12

With the gradual reduction of available filling materials and the increase of filling costs, many coal mines now use the strip mining method to mine 3U coal seams. Strip mining is a partial mining method in which the overlying strata and surface subsidence can be effectively controlled. This effective technical method has been widely used in many mining areas in eastern China. Combined with the advantages of the filling method and the strip method, strip filling mining can control surface subsidence well.13-16 The demand for filling materials in strip filling mining is low, which can greatly reduce the filling cost. At the same time, strip filling mining has overcome the shortcomings of a low coal mining rate, with more than 90% of coal accounted for.17-19

The similar material simulation test is an effective method to study practical problems in mining engineering. Physical models, consisting of sand and plaster and obeying relevant similarity rules, were used to investigate the subsidence mechanisms from the sequential extraction of overlapping coal longwall panels.20,21 An orthogonal study was conducted on low-strength similar materials including sand, fly ash, and plaster, the sensitivity of the materials was analyzed, and strip filling mining in a coal mine in eastern China was simulated.22-24

In the process of mining engineering, a rock mass is subjected to continuous loading and unloading under polyaxial stress states.25-30 The stress-strain characteristics of the rock mass showed different mechanical responses with changes in the mining sequence.31,32 Gong et al33 adopted an analytic hierarchy process (AHP) with a fuzzy comprehensive evaluation method to study the underground mining method sequence. The excavation sequence of long-span coal roadways is the key factor to the stability of the roadway. Large sections of full coal roadways have an obvious influence on the failure area, stress distribution, and displacement of the surrounding rock. The first excavation of the large section is beneficial to the stability of the two coal bodies, while the first excavation of the small section is beneficial to the stability of the top plate.34

In summary, scholars have done a substantial amount of research on strip filling mining. However, there is a lack of research on the influence of strip mining and the filling sequence on surface subsidence in coal mining. In strip filling mining, there are two mining sequences: first mining and then filling or first filling and then mining. The determination of a reasonable mining sequence in controlling surface subsidence is an important problem in strip filling mining. In this paper, the west 510 mining area of the Liudong Coal Mine was selected as the engineering background. Through theoretical analysis, laboratory tests, and numerical simulations, the stress distribution of the filling body (or coal pillar) and the surface subsidence under different filling mining sequences were tested and analyzed, and the better mining sequence was obtained. This paper is intended to provide the mining and filling sequence that is more conducive to controlling mining damage to enhance the environmental protection benefits of strip filling mining and expand the application range of strip filling mining without increasing mining costs.

2 | ENGINEERING BACKGROUND AND THEORETICAL DESIGN

2.1 | Engineering background

The Liudong Coal Mine is located in Huaihe City, Anhui Province, China. The north-south length is approximately 6 km, the east-west width is approximately 2.5 km, and the area is approximately 18.6239 km². The relevant geographic information is shown in Figure 1.

According to drilling and geophysical data, the strata seen in the coal field include Ordovician, Permian Benxi formation, Taiyuan formation, Permian Shanxi formation, upper and lower Shihezi formation, and Quaternary system. The Quaternary thickness is 83.6-126.0 m, and the average thickness is 98.0 m. The ground elevation in this area is approximately 32.0 m, and the west 510 mining area is mainly focused on mining No.10 coal seams. The mining elevation is approximately 380.0 to 590.0 m, and the average buried depth is 420 m. The occurrence of 10 coal seams is stable, the thickness varies from 0.9 to 4.3 m, with an average of 3.0 m, and the dip...
angle of the coal seams is 7°-33°, with an average of 20°. The occurrence information of the No. 10 coal seam roof and floor in the west 510 mining area is shown in Figure 2.

The west 510 mining area of the Liudong Coal Mine is the first mining area of No. 10 coal in the west wing of the coal mine. There are many surface buildings, as shown in Figure 1. The Liu Dong Coal Mine cannot bear the high costs of fully adopting filling mining; in addition, filling mining technology is complex, occupies more people, and has a low output. Therefore, the strip filling mining method has been adopted at the Liudong Coal Mine.

2.2 | Theoretical design

Based on the data of drilling and geophysical exploration, based on the analysis of rock structure in the west 510 mining area of Liudong Coal Mine, the position of the key strata

| Columnar section | Slice thickness/m | Buried depth/m | Rock name | Lithological description                                                                 |
|------------------|------------------|----------------|-----------|-----------------------------------------------------------------------------------------|
| 10.0~13.0       | 12.0             | 388.3          | Fine sandstone | The lithology belongs to a combination of gray and gray-white fine sandstone, and comprises medium-grained sandstone in local positions. |
| 5.0~7.0         | 6.2              | 400.3          | Siltstone   | Gray, silty structure, medium-thick layered structure, uneven fracture, horizontal bedding development |
| 9.0~11.0        | 10.0             | 406.5          | Sandstone   | Broken, fissure development, low mechanical strength, localized alternating of siltstone and fine sandstone |
| 3.0~4.0         | 3.5              | 416.5          | Mudstone    | Gray-black, shale structure, thin layered structure, staggered fracture, core breakage.    |
| 0.9~4.3         | 3.0              | 420.0          | No.10 coal  | Black, crack development, low mechanical properties.                                    |
| 2.0~3.0         | 2.3              | 423.0          | Fine sandstone | Fine sandstone with carbonaceous and mica fragments on the level, with horizontal bedding |
| 7.0~8.5         | 7.8              | 425.3          | Siltstone   | Gray, dense, with diamonds, with discontinuous wavy horizontal bedding, mainly composed of quartz, partially fine sandstone, clear layer |

**FIGURE 1** Liu Dong coal mine geographic information map

**FIGURE 2** The characteristics of the rock formation
of overlying rocks is distinguished according to the theory of Key Strata. The results show that the main key layer of overburden rock is fine sandstone from 84-92 m above No.10 coal seam. According to the estimation results of fracture distance of overlying key layer, in order to ensure that the main key layer of overlying rock does not break, the mining width of short wall working face should be less than 60.3 m. Considering the occurrence change of the main key strata of overlying rock and the error of the estimated break distance, the mining efficiency of the coal mine is taken into account, and the strip mining width is determined to be 55 m.

The structural mechanics equation can be obtained as

\[
\frac{1}{2} \pi \left( \frac{L_0}{2} \right)^2 C_x \gamma = \frac{e}{2b} L_0 C_x q \times 100 \tag{1}
\]

where \( L_0 \) is the length of the working face, m; \( C_x \) is the working face advancing distance, m; \( \gamma \) is the bulk density of the rock strata, \( \text{t/m}^3 \); \( e \) is the strip filling length, m; \( 2b \) is the filling strip spacing, m; and \( q \) is the uniform stress distribution load of the filling strip, MPa.

According to Equation 1, the uniformly distributed load of the strip filling is

\[
q = \frac{\pi L_0 b \gamma}{400 e} \tag{2}
\]

Therefore, the strength design criterion of a strip filling body in single working face mining is

\[
a = \lambda \frac{\pi L_0 b \gamma}{400 e} \tag{3}
\]

where \( a \) is the filling strength, MPa; and \( \lambda \) is a safety factor. In this paper, the length of a single stope face is equal to that of two short wall working faces, that is, \( L_0 = 110 \text{ m}, \gamma = 2.5 \text{ t/m}^3, e = 55 \text{ m}, 2b = 110 \text{ m}, \lambda = 1.5 \), and the strength of the filling body \( a = 3.24 \text{ MPa} \).

Two mining sequences of the strip filling mining mode are set in the west 510 mining area of the Liudong Coal Mine. Order 1 involves first mining and then filling. In this sequence, strip mining is completed first, and then, a paste filling replacement is used to mine strip the coal pillars. Order 2 involves first filling and then mining. In this sequence, the middle working face is filled first, and then, both sides of the working face are mined by the caving method. The mining sequences of the two mining modes in the west 510 mining area are shown in Figure 4. The two different mining sequences will inevitably lead to different degrees of movement of the overlying strata in the working face. To reproduce these two mining sequences and to further investigate the stability of the overlying strata, the similar material simulation test was used to study the force of the filling body (or coal pillar) and the surface subsidence caused by the two mining methods. The profile simulated by the similar simulation test is perpendicular to the advancing direction of the coal seam.

3 | PREPARATION OF LOW-STRENGTH SIMILAR PASTE FILLING MATERIAL

The proportion of similar materials greatly influences the physical and mechanical properties of the model materials. Although similar materials have been widely applied, these materials are seldom suitable for backfill mining. Additionally, the backfill body has a lower strength than the coal-bearing sedimentary rocks. Thus, it is significant to study similar materials with lower strengths.\(^{22,23}\) Therefore, a low-strength similar paste filling material was developed for the paste properties of the Liudong Coal Mine.

3.1 | Design of proportioning test

According to the filling materials used in the Liudong Coal Mine, the materials in the experimental study of the similar material ratio were fly ash, gypsum, and sand. Given that the compressive strength of the similar materials used in the simulation tests is low, the proportion of similar materials with a large cement ratio and a large sand-binder ratio was considered. The test was designed according to the two-factor and four-level orthogonal table, as shown in Table 1. A total of 3
16 groups of proportioning schemes were designed by the orthogonal test, as shown in Table 2.

The uniformly stirred filling material with a mass concentration of 80% was put into the mold and tamped, and standard specimens with Φ 50 × 100 mm were made after demolding. The standard specimens are shown in Figure 5.

### TABLE 1  Orthogonal design level of similar materials

| Level | Sand-binder ratio (A) | Cement ratio | Fly ash: gypsum (B) |
|-------|-----------------------|--------------|---------------------|
| 1     | 6:1                   | 8:2          |                     |
| 2     | 7:1                   | 7:3          |                     |
| 3     | 8:1                   | 6:4          |                     |
| 4     | 9:1                   | 5:5          |                     |

3.2 | Analysis of uniaxial compression test results

Uniaxial compression tests were carried out on 16 groups of specimens by an electronic Shimadzu Autograph (AGX-250) universal testing machine. The uniaxial compressive strengths and elastic moduli of the similar materials under different ratios were obtained, as shown in Table 3. The number denoting the mixing ratio comprises three digits. Taking the number “682” as an example, the mass ratio is 6:0.8:0.2 and is abbreviated for simplicity; “6” represents the sand-binder ratio, and “82” represents the cement ratio. Some typical similar material specimens after failure are shown in Figure 6.

The uniaxial compressive strengths of the similar materials with different mixing ratios varied from 28.542 to 100.407 kPa, and the elastic moduli varied between 813.918 and 4008.291 kPa. These values meet the requirements of
the lower strength similar material simulation tests. Figure 7 shows a plot of the stress-strain curve of the similar materials with different cement ratios under a constant sand-binder ratio. It can be clearly seen that the strength of the similar materials experiences a decrease as the sand-binder ratio increases. Figure 8 shows the total stress-strain curve of the similar materials with different sand-binder ratios under a constant sand-binder ratio. Similar to the previous index, the strengths of the similar materials clearly show a decrease as the cement ratio increases.

According to the similarity theory, the stress similarity constant was selected as 150, which will be described in detail in the fourth section. The compression strength of the backfill paste obtained by theoretical calculations for the Liudong Coal Mine was 3.24 MPa. Therefore, the strength of the similar material should be 21.6 kPa. It can be seen from Table 3 that the strength of the P41 group is closest to this value. This ratio uses less cement and has a low cost. Therefore, the mixing ratio of the similar material should be 9:8:2. A filling block with dimensions of 5 × 22 × 2.9 cm was made with this weight ratio (sand: fly ash: gypsum = 9:0.8:0.2). The block was removed from the mold after the initial setting and placed into the area to be filled in time. The prepared filling block is shown in Figure 9.

### TABLE 2 Orthogonal test scheme

| Scheme | Factor | Cement ratio | Ratio number |
|--------|--------|--------------|--------------|
| 1      | A1     | B1           | 682          |
| 2      | A1     | B2           | 673          |
| 3      | A1     | B3           | 664          |
| 4      | A1     | B4           | 655          |
| 5      | A2     | B1           | 782          |
| 6      | A2     | B2           | 773          |
| 7      | A2     | B3           | 764          |
| 8      | A2     | B4           | 755          |
| 9      | A3     | B1           | 882          |
| 10     | A3     | B2           | 873          |
| 11     | A3     | B3           | 864          |
| 12     | A3     | B4           | 855          |
| 13     | A4     | B1           | 982          |
| 14     | A4     | B2           | 973          |
| 15     | A4     | B3           | 964          |
| 16     | A4     | B4           | 955          |

FIGURE 5 Standard specimens

4 | SIMILAR SIMULATION TESTS ON DIFFERENT MINING AND FILLING SEQUENCES

4.1 | Testing scheme

4.1.1 | Selection of similarity constant and similar material ratio

To capture the realistic behavior of a rock mass via physical modeling techniques, physical models should be developed in accordance with the principles of similarity theory. The model used in the test is a plane strain model, with dimensions of 1.9 × 1.6 × 0.22 m. According to the requirements of the test, the geometric similarity constant is determined to be $C_g = \frac{1}{100}$, the density similarity constant is determined to be $C_\rho = \frac{1}{1.5}$, and the strength similarity constant is $C_\sigma = \frac{1}{150}$.

According to field data of prototype coal and rock strata, sand is used as an aggregate and fly ash and gypsum are used as bonding materials in the model. The material ratio is selected according to the compressive strength of the laying
strata, as shown in Table 4. The doses of sand, fly ash, and gypsum were calculated according to the size and thickness of the model. The physical model was 190 cm long, 157 cm tall, and 22 cm wide. All the layers in the model were laid from bottom to top until the model was formed.

### 4.1.2 Monitoring program and instruments

**Observation of stope displacement**

There are seven displacement measuring lines (located at 10, 15, 20, 25, 30, 35, and 40 cm above the coal seam, respectively) arranged as shown in Figure 10. The measuring lines are L1, L2, L3, L4, L5, L6, and L7 from the bottom to the top. The total station is used to regularly observe the displacement change of each measuring point after mining.

**Observation of stope stress**

The stress of the filling stope was measured by a BW foil resistance strain micro pressure box. A total of 15 pressure boxes are arranged in the coal seam floor of test 1 (mining sequence 1, that is, mining first and then filling). A total of 29 pressure boxes are arranged in the coal seam floor of test 2 (mining sequence II, that is, filling first and then mining). The sensor arrangements of the two mining methods are shown in Figure 10. The pressure box is basically symmetrical on the left and the right, which can correct each other. The sensor arrangement and data acquisition system after the model has been laid are shown in Figure 9.

### 4.2 Results and analysis of displacement monitoring

For mining scheme 1, the mining sequence is 51001 → 51005 → 51003, and the mining sequence for mining scheme 2 is 51003 → 51001 → 51005. For the filling working face, in each mining and filling cycle, the initially condensed filling block is put into the filling area in time after coal seam mining. The mining of the final overlying rock shape of the model after the mining and filling activities is shown in Figure 11.

#### 4.2.1 Displacement monitoring results

The position of each displacement measuring point in the mining process was observed by using the total station instrument. According to the observation results, the subsidence curves of 51001, 51003 (filling) and 51005 in the two mining schemes are shown in Figures 12 and 13.

#### 4.2.2 Analysis of displacement monitoring

By comparing the two mining schemes, it can be found that the subsidence value of each measuring point after scheme 2 mining is generally smaller than that of scheme 1 mining. In particular, the subsidence of each measuring point above the

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**TABLE 3** Uniaxial compression test results of similar materials\(^{22,23}\)

| Specimen number | Ratio | UCS (kPa) | E (kPa)  |
|-----------------|-------|-----------|----------|
| P11             | 682   | 51.93     | 1110.083 |
| P12             | 673   | 58.388    | 1754.256 |
| P13             | 664   | 78.818    | 3401.377 |
| P14             | 655   | 100.407   | 4008.291 |
| P21             | 782   | 44.10     | 961.323  |
| P22             | 773   | 52.478    | 1698.07  |
| P23             | 764   | 64.009    | 2629.804 |
| P24             | 755   | 88.60     | 3862.366 |
| P31             | 882   | 37.667    | 830.82   |
| P32             | 873   | 43.958    | 1548.728 |
| P33             | 864   | 53.935    | 2252.316 |
| P34             | 855   | 72.092    | 3480.833 |
| P41             | 982   | 28.542    | 813.918  |
| P42             | 973   | 38.673    | 1311.437 |
| P43             | 964   | 48.199    | 2133.269 |
| P44             | 955   | 58.487    | 2941.296 |

**FIGURE 6** Partial specimens after test failure

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\(\text{UCS}\) stands for uniaxial compressive strength, \(\text{E}\) stands for Young's modulus.
51003 (filling) working face is obviously smaller than that of scheme 1 mining because an isolated island working face is formed when using scheme 1 in the 51003 working face, and the pressure of the working face is large. After mining, the movement speed of the overlying strata increases under the action of pressure, and the overlying strata act quickly on the filling body. The deformation of the filling body increases before its strength is brought into full play, and the final control effect on the movement of the overlying strata is reduced. If the surrounding working face continues to use scheme 1 mining, the influence range of mining will be further enlarged, and the subsidence of the ground is larger than that of mining scheme 2, which is disadvantageous to the control of surface deformation and the protection of surface buildings.

It can be clearly seen from Figure 11 that in the roof near the coal seam, the damage of scheme 2 is more serious, and the displacement monitoring subsidence is larger than that of scheme 1 mining because in the mining process of scheme 2, after filling and mining in the middle working face, when mining on both sides of the working face, the roof failure forms are cantilever beams. However, in the mining process of scheme 1, the roof failures of the working face on both sides have the form of embedded beams. Therefore, the roof damage near coal seam in scheme 2 mining is more serious, but the displacement near the surface is still large in scheme 1.

4.3 | Results and analysis of abutment stress monitoring

4.3.1 | Abutment stress monitoring results

Mining scheme 1
In the process of mining, the coal pillar force of the 51003 working face and the filling body force of the 51003 filling face are monitored for a long time, and the monitoring results are shown in Figure 14.

Mining scheme 2
In the process of mining scheme 2, the abutment stress of the coal pillars in the 51001 and 51005 working faces after filling mining the 51003 working face and the goaf and filling body force after final mining were monitored, and the results are shown in Figure 15.
4.3.2 | Analysis of abutment stress monitoring results

Mining scheme 1

It can be seen from Figure 14 that after mining the 51001 and 51005 working faces, the abutment pressure of the coal pillar (that is, the 51003 working face) is obviously larger than that of the filling body after the 51003 working face was recovered and filled. The main reason is that the mining mode is strip mining before the 51003 working face is exploited. The stress arch structure Ⅰ will be formed after mining the 51003 working face, as shown in Figure 16A. The weight of the
overlying strata will be transferred to the surrounding coal pillar, and the overlying strata will be supported by the coal pillar, so the stress of the coal pillar will be greater than that of the original rock at this time. The ultimate force of the filling body is less than that of the coal pillar before mining.

Due to the movement of the overlying strata and the secondary activation of the surrounding goaf caused by filling mining in the 51003 working face, a new stress arch structure II is formed in the similar simulation test, as shown in Figure 16B. A part of the overlying strata can be supported by the stress arch, and the load on the filling body is only the rock weight in the range of the stress arch.

**Mining scheme 2**
As shown in Figure 15, after filling mining the 51003 working face, the edge abutment stresses in the goaf of the 51001 and 51005 working faces increase, but the abutment stress of the filling body is much smaller than that of the original rock stress, and the force of the filling body is uneven. Because part of the rock layer affected by mining is supported by the filling body, the movement of the rock layer is limited, so that the influence range of mining is greatly reduced. Therefore, the stress arch III shown in Figure 17A is finally formed, which results in the increase of the edge stresses of the 51001 and 51003 coal pillars, and the stress on the filling body is less than that of the original rock. The uneven force of the filling body may be caused by the different thicknesses of the filling body. After mining the 51001 working face, the stress arch V shown in Figure 17B is formed immediately, which results in the decrease of the stresses of the 51001 mined area and 51003 filling body.

From Figure 15, after the mining of scheme 2, the abutment stress of the filling body is obviously increased, and the stress at the edge of the filling body is larger than that before mining. However, the stress in the middle part of the filling body and the average stress are still smaller than the stress in the original rock, but the stress at the edge of the goaf is very small due to the formation of the stress arch structure shown in Figure 17C. The total amount of overlying strata is transferred to the solid coal or filling body at the arch foot through the stress arch, resulting in the stress increase.

### Table 4 Model material ratio and laying level

| Number | Lithology          | Rock layer thickness (cm) | Repeat thickness (cm) | Repeat times | Material ratio |
|--------|---------------------|---------------------------|-----------------------|--------------|---------------|
| R20    | Siltite             | 26                        | 2                     | 13           | 7:5:5         |
| R19    | Fine sandstone      | 6                         | 2                     | 3            | 7:8:2         |
| R18    | Mud stone           | 4                         | 2                     | 2            | 8:6:4         |
| R17    | Fine sandstone      | 8                         | 2                     | 4            | 7:8:2         |
| R16    | Mud stone           | 3                         | 1.5                   | 2            | 8:6:4         |
| R15    | Siltite             | 4                         | 2                     | 2            | 7:5:5         |
| R14    | Mud stone           | 5                         | 2.5                   | 2            | 8:6:4         |
| R13    | Fine sandstone      | 4                         | 2                     | 2            | 7:8:2         |
| R12    | Mud stone           | 3                         | 1.5                   | 2            | 8:6:4         |
| R11    | Fine sandstone      | 3                         | 1.5                   | 2            | 7:8:2         |
| R10    | Mud stone           | 6                         | 2                     | 3            | 8:6:4         |
| R9     | Silty mudstone      | 4                         | 2                     | 2            | 8:6:4         |
| R8     | Bauxite mudstone    | 3                         | 1.5                   | 2            | 8:6:4         |
| R7     | Mud stone           | 10                        | 2                     | 5            | 8:6:4         |
| R6     | Fine sandstone      | 3                         | 1.5                   | 2            | 7:8:2         |
| R5     | Mud stone           | 4                         | 2                     | 2            | 8:6:4         |
| R4     | Fine sandstone      | 12                        | 2                     | 6            | 7:8:2         |
| R3     | Siltite             | 6                         | 1.5                   | 4            | 7:5:5         |
| R2     | Siltstone and sandstone | 10                     | 2                     | 5            | 8:6:4         |
| R1     | Mud stone           | 4                         | 1                     | 4            | 8:6:4         |
| M      | No.10 coal          | 3                         | 3                     | 1            | 8:6:4         |
| F1     | Fine sandstone      | 2                         | 2                     | 1            | 7:8:2         |
| F2     | Siltite             | 8                         | 2                     | 4            | 7:5:5         |
| F3     | Medium sandstone    | 4                         | 2                     | 2            | 7:7:3         |
| F4     | Mud stone           | 6                         | 3                     | 2            | 8:6:4         |
It can be seen from Figure 18 that the stress level of the filling body after mining with scheme 1 is higher than that after mining with scheme 2. The main reasons are that the movement time of the overlying strata is shortened in scheme 2, the setting time of the filling body is less, and the compression deformation of the filling body increases in the early stage.
because of the formation of an isolated island coal pillar in the mining process of scheme 1. In the process of scheme 1 mining, the movement space of the overlying strata increases correspondingly, the range of the formed stress arch increases, and the stress acting on the filling body increases. During the test, the middle and average stresses of the filling body are less than those of the original rock stress mainly because the stress arch is formed due to the limited mining range (size effect), and the stress arch bears the weight of part of the overlying strata. For the west 510 mining area of the Liudong Coal Mine, the large stress arch will no longer exist, and the filling body will have a larger force than that measured in the laboratory (the middle and average stresses of the filling body will be close to or even greater than the original rock stress).

To further discuss the distribution of stress and the plastic zone under the two mining schemes, the influences of the different mining and filling sequences on surface subsidence and the stability of the strip filling body were studied by numerical simulation software FLAC3D. The numerical model was 300 m long × 100 m wide × 260 m high. The total length of the working face was 55 × 3 m. To eliminate the boundary effect, two pillars with a width of 67.5 m were
established on each side of the model. The simulated excavation strike length was 80 m, and there was a coal pillar of 20 m on the back of the model. The model height was 145 m. The stress boundary was above the model, a vertical stress of 10 MPa was applied and set the bottom and surroundings of the model as fixed boundaries, the lateral pressure coefficient is 1, and the thickness of the simulated coal seam was 3 m.

First, the Mohr-Coulomb model is selected to generate the initial stress field according to the above constraints, and then the displacement field and velocity field are cleared after equilibrium, and then, the coal seam mining is carried out, which is similar to the simulation test of similar materials. For the strip filling scheme, there are the following two schemes:

**FIGURE 16** The evolution process of the stress arches of mining scheme 1

**FIGURE 17** The evolution process of the stress arches of mining scheme 2
Scheme 1: First mining and then filling, strip mining 51001 and 51005 working face firstly, and then filling replacement 51003 working face. The collapse of the direct roof is simulated by null element model and does not participate in the calculation. The filling mining space is simulated by Mohr-Coulomb model, and its filling space is used to participate in the calculation. Finally, the elastoplastic solution of Mohr-Coulomb model is carried out until the system reaches equilibrium.

Scheme 2: First filling and then mining, the parameters of the filling body, the calculation step number should be the same as the first mining and then filling.

The selection of physical and mechanical strength parameters of rock mass is based on the manual of rock mechanics parameters and the classification standard of engineering rock mass. The dimensions and parameters of the specific coal seam and each strata are no longer introduced in detail. According to the experimental results of mechanical properties of paste filling materials, the mechanical parameters of filling materials are shown in Table 5.

Figure 19 shows the vertical stresses in the middle of the goaf of the two schemes after the final mining. The vertical stress at a height of 4 m from the coal seam was monitored, and the stress distribution diagram is shown in Figure 20.

It can be seen from Figures 19 and 20 that the vertical stress distributions of the two mining schemes are basically the same, and the maximum stresses are almost equal. In particular, in the area of caving mining on both sides, the vertical stresses almost coincide. There is a significant difference in the vertical stress distributions at the filling paste. The vertical stress of scheme 2 is obviously smaller than that of scheme 1. This condition is advantageous for the stability of the filling paste. The vertical stresses on both sides of the coal pillar of scheme 2 are slightly larger than those of scheme 1, but this has little effect on the original rock.

Generally, the vertical stresses formed by the two schemes show different trends in the middle of the filling body, and the vertical stress of scheme 2 is smaller than that of scheme 1, which is more advantageous for the stability of the filling paste body.
As seen from Figure 21, the whole filling body of scheme 1 is in the plastic zone, while a small part of the filling body of scheme 2 is in the plastic zone, which indicates that the elastic core area that actually plays a supporting role in scheme 1 is less than that of scheme 2, so the effect of scheme 1 on controlling surface subsidence is worse than that of scheme 2. Therefore, without considering other factors, scheme 2 should be adopted as much as possible, that is, filling mining should be done first and then strip mining should be done to avoid the formation of isolated island working faces in the process of mining. Moreover, filling mining is simple and keeps roadways along the goaf, which plays an important role in reducing roadway excavation. Under the same mining technology, the amount of surface movement and deformation can be reduced accordingly.

In order to determine the rationality of the strip filling mining scheme in Liudong Coal Mine and realize the safe and efficient production of the coal mine, the surface subsidence of Liudong Coal Mine was observed. The survey area is located in the west of Huaibei City. The north and south of the survey area is about 2.6 km, the east and west width is about 4.6 km, and the overall area of the survey area is about 12 km², the layout of the measuring points is shown in Figure 22. The maximum subsidence of the measuring point is 355.6 mm, and the settlement rate of the observation point above the goaf face is within the national standard range of 0.04 mm/d. The observation results of surface subsidence show that the strip filling mining in Liudong Coal Mine is reasonable.

5 | CONCLUSIONS

According to the actual engineering background of the west 510 mining area in the Liudong Coal Mine, the control effect
of different mining sequences on the overlying rock and the stress of the filling body are compared and studied by using simulation tests, and the following conclusions are obtained.

1. When the strength of the strip filling body reaches 3.24 MPa, the strip filling body can safely support the rock weight in the cracked arch and effectively control the surface subsidence.
2. A paste filling material, which has mechanics similar to those of the gypsum filling material used in the Liudong Coal Mine, is obtained. The ratio of sand: fly ash: gypsum is 8.0:8.0:2.
3. Mining before filling will increase the movement speed and range of overlying strata due to the formation of isolated island working faces in the process of mining and ultimately increase the stress, surface movement, and deformation acting on the filling body.
4. The elastic core area of the filling body of scheme 2 is larger than that of scheme 1, and compared with scheme 2, the plastic zone of the scheme 1 filling body expands more in the horizontal direction than that of the scheme 2 filling body.
5. Scheme 2 (mining before filling) is better than scheme 1 (mining before filling) in controlling the subsidence effect. Under the same mining technology, the mining-induced failure of scheme 2 can be reduced.

CONFLICTS OF INTEREST
The authors declare no conflict of interest.

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