INTRODUCTION

Mining-induced subsidence is a recurring source of damage to built features, assets, surface and underground water resources, and other environmental features. In northwest China, the majority of mining areas are located within or on the edges of deserts, which often have shallow coal seam reserves and attractive conditions for mining. However, these areas also have arid and semiarid climates with fragile ecological environments and significant water shortages. Yushen Coalfield, located in northwest China, has three to five primary coal seams; overall, it is categorized as multiseam mining. Engineering has revealed two major problems resulting from multiseam mining: First, concentrated stress is caused by coal pillars, which results in decreased roadway support; second, major ground surface fractures are generated by repetitive mining. Mining can cause the surface to develop uneven subsidence, as well as cause significant ecological destruction. Therefore, exploration of effective mining of multiple coal seams while reducing surface damage and surface water loss is a key issue, one that needs to be solved urgently.
Previous research has shown that there are noticeable differences in surface subsidence between single and multiseam coal mining. Multiseam mining aggravates roof damage, which leads to an increase in the fracture range of overburden strata. Physical experiments and numerical simulation were used to predict and analyze the influence of mining-induced subsidence on surface structure. To explore the effects of ground deformation resulting from shallow-buried, close-distance, multiseam mining, periodic variation in parameters was measured and recorded related to ground subsidence and surface cracks.

Multiseam mining not only causes surface subsidence, but also has a significant influence on mining-induced stress environment for mining. This causes stress and the fractured water-conducting zone redistribution of the overburden strata around the working face. To avoid stress concentration and the superposition of the surface subsidence of multiseam mining, the distance between the right boundary of the upper coal layer pillar and the left boundary of the lower coal layer pillar is considered to be the staggered mining distance. Under multiseam mining conditions, the layout of coal pillars has a significant effect on overburden strata stress and surface subsidence. However, further research is needed on how to effectively solve problems related to water retention and loss reduction, through staggered distance layout and optimization of coal pillars.

In view of these issues, for the background in this study we used the Xiaobaodang Coal Mine in Yushen Coalfield, in which multiseam mining occurs. We used theoretical analysis and numerical and physical simulation to systematically investigate the reasonable staggered distance of the coal pillar layout in multiseam mining. Additionally, we analyzed overburden strata stress distribution, Z displacement of the coal pillar center, and the surface subsidence curve, in order to compare different schemes and select the optimization scheme. Optimization of staggered distance mining schemes could allow us to effectively solve the problems of water retention and loss reduction.

2 | THEORETICAL ANALYSIS

Due to the complexity of coal seam burial, the shallow coal seam, gravity stress, and tectonic stress are small. Following coal seam mining, the concentrated stress of the coal pillar is less than the strength of the same pillar; additionally, most of the coal pillars have shifted to the elastic state. However, for deep-buried coal seams, as a result of high overburden strata stress and complex stress distribution, plastic deformation often occurs in coal pillars after coal mining. Moreover, the failure process of coal rock is nonuniform, noncontinuous, and nonlinear. In order to better adapt the theoretical analysis to the occurrence state of the coal seam, the coal pillar of multiseam staggered distance mining should be analyzed in both the elastic and plastic states.

2.1 | Analysis of the staggered distance for multiseam mining based on the elastic theory

We avoided the high-stress transfer area of the upper coal, reduced the stress concentration, and ensured the safety and stability of the coal pillar in the lower coal section by using the reasonable staggered distance of the coal pillar. Here, \( l_{\text{min}} \) is the minimum staggered distance for multiseam mining, which represents the stress transfer of the coal pillar, satisfying the values of \( X \) at \( \sigma_x \leq 0.1q, \sigma_z \leq 0.1q, \) and \( \tau_{xz} \leq 0.1q, \) where \( q \) is the stress at the center of the coal pillar, \( X \) is the horizontal distance under the safety condition, \( \sigma_x \) is the horizontal stress, \( \sigma_z \) is the vertical stress, and \( \tau_{xz} \) is the shear stress.

However, an increase in the staggered distance for the coal pillar may cause the lower section pillar to enter the high-stress area in the middle of the upper coal goaf. Therefore, \( l_{\text{max}} \) is the maximum staggered distance for the lower coal seam, in order to avoid the high-stress area in the middle of the upper coal goaf.

2.1.1 | Analysis of staggered distance based on stress transmission effect of the upper coal pillar

Because of the support provided to the section coal pillar, upper coal mining leads to stress concentration in the coal pillar area. At the same time, in a certain range of the coal pillar, the floor strata produce a high-stress transfer area.

When studying the staggered distance arrangement of double-seam mining, it should be understood that the upper coal area has only two mine working faces. Because of the pressure relief provided by the upper coal mining and the support of the coal pillar, the stress acting on the interlayer rock mass and the lower coal pillar is considerably less than its rock compression and shear strength. Therefore, the interlayer rock mass and the coal pillar in the lower coal section can be regarded as semi-infinite elastic bodies. Moreover, the influence of coal pillar stress in the upper coal section on the coal pillar in the lower coal section can be simplified as a plane strain problem. Because it is a plane problem, the independent stress components that need to be calculated are only \( \sigma_x, \sigma_z, \) and \( \tau_{xz} \):

\[
\begin{align*}
\sigma_x &= \frac{2x^2}{(x^2 + z^2)^2} \frac{2F}{\pi} \\
\sigma_z &= \frac{2z^3}{(x^2 + z^2)^2} \frac{2F}{\pi} \\
\tau_{xz} &= \frac{2z^2}{(x^2 + z^2)^2} \frac{2F}{\pi}
\end{align*}
\]  (1)
In order to address the research problem: (a) The stress change in the width of the upper coal pillar should be ignored, as its value is the most unfavorable case \( q = k\gamma H \), where \( k \) is the stress concentration factor, which is generally between 5 and 15; (b) the force on the floor of the upper coal pillar can be simplified as the uniform strip load.

As shown in Figure 1, taking the center of a coal pillar as the coordinate origin, we have \( B \) as the pillar width \((B = 2b)\) and \( q \) as the stress in the width of the upper coal pillar; the mechanical calculation model was established using the length \( X \) and the depth \( Z \) from the coal pillar to the ground.

A small length should be considered on the coal pillar from the coordinate origin \( O \) at a distance of \( \xi \), and consider the force on it as a small concentrated force. The three stress components caused by this small concentrated force can be expressed as follows:

\[
\begin{align*}
\sigma_x &= \frac{2q}{\pi} \frac{z\xi^2}{(x^2 + z^2)^2} \\
\sigma_z &= \frac{2q}{\pi} \frac{z^3}{(x^2 + z^2)^2} \\
\tau_{xz} &= \frac{2q}{\pi} \frac{xz^2}{(x^2 + z^2)^2}
\end{align*}
\]  

Upon integration of Equation (2) with the width of the coal pillar, the stress expression in the rock stratum of the coal pillar floor can be obtained under the uniform load as follows:

\[
\begin{align*}
\sigma_x &= \frac{2q}{\pi} \int_{-b}^{b} \frac{z(x - \xi)^2}{(x - \xi)^2 + z^2} d\xi \\
\sigma_z &= \frac{2q}{\pi} \int_{-b}^{b} \frac{z^3}{(x - \xi)^2 + z^2} d\xi \\
\tau_{xz} &= \frac{2q}{\pi} \int_{-b}^{b} \frac{(x - \xi)z^2}{(x - \xi)^2 + z^2} d\xi
\end{align*}
\]  

Integrate Equation (3) and simplify it to obtain the following:

\[
\begin{align*}
\sigma_x &= \frac{q}{\pi} \left[ \arctan \frac{x + b}{z} - \arctan \frac{x - b}{z} \right] \\
\sigma_z &= \frac{q}{\pi} \left[ \arctan \frac{x + b}{z} + \arctan \frac{x - b}{z} \right] \\
\tau_{xz} &= \frac{q}{\pi} \left[ \frac{z^2}{z^2 + (x + b)^2} - \frac{z^2}{z^2 + (x - b)^2} \right]
\end{align*}
\]  

(4)

According to a large number of engineering practices, when the concentrated load \( F \leq 0.1(\sigma_x, \sigma_z, \text{ or } \tau_{xz}) \), which is transmitted downward from the upper coal pillar, is taken into consideration it indicates that the lower pillar has avoided the stress concentration region of the upper coal pillar; at this time, the inverse solution horizontal transmission distance \( X \), \( X \) corresponds to \( l_{\text{min}} \).

\[ l_{\text{min}} = \max \{0.1X_{\sigma_x}, 0.1X_{\sigma_z}, 0.1X_{\tau_{xz}}\} \]  

(5)

2.1.2 Analysis of staggered distance values based on the influence of compacted goaf of upper coal

With the increase in the staggered distance of the coal pillars in the upper and lower coal seam sections, the lower coal pillars avoid the stress influence area of the upper coal pillars, but the lower coal pillars may enter the high-pressure stress area in the middle of the upper goaf. To avoid this, the staggered distance of the coal pillars should meet the following needs: \( l \leq l_{\text{max}} \). The stress transfer model of the compacted goaf was established as shown in Figure 2.

Because of the symmetry of the research problem, half of the goaf as the research object can be obtained as follows:

\[
l_{\text{max}} = \frac{1}{2} L - \frac{1}{2} \lambda L - B - H \tan \phi \]  

(6)

where \( l_{\text{max}} \) is the maximum staggered distance of the coal pillars (unit: m), \( L \) is the upper coal seam working face width (unit: m), \( \lambda \) is the compaction width coefficient of the goaf in the upper coal seam (unit: m), \( B \) is the pillar width of the lower coal seam (unit: m), \( H \) is the distance between the upper and the lower coal seams (unit: m), and \( \phi \) is the concentrated stress transfer angle in the goaf compaction area (unit: °).

Based on the analysis results from Sections 1.1 and 1.2, in order to avoid the influence of the concentrated stress of the coal pillar in the upper section and the high-pressure stress in the middle of the goaf, the reasonable staggered distance \( l \) of the coal pillar should be as follows:

\[ l_{\text{min}} \leq l \leq l_{\text{max}} \]  

(7)
2.2 Analysis of staggered distance values for multiseam mining based on plastic slip line field theory

The plastic slip line field theory can be used to obtain the stress field, deformation velocity field, and the corresponding limit load in the limit equilibrium state. After coal mining in the upper layer, the coal pillars in the relevant section generate stress concentration. Because the height of a coal pillar in a particular section is considerably smaller than the thickness of the interlayer, the stress between the coal pillar in the upper section and its lower layer can be regarded as the stress model of the strip foundation acting on the semirigid foundation.

According to the “high compressive strength and low tensile strength” properties of rock, the staggered distance mining model of the coal seam group can be established on the basis of soil mechanics and the theory of the plastic slip line field (shown in Figure 3), in which area I is the active zone of stress, area III is the passive zone of stress, and area II is the transition zone of stress. The BC stress slip line is an elastic-plastic interface and is a logarithmic spiral. The trajectory equation is as follows:

\[ r = r_0 e^{\theta \tan \phi} \]  

(8)

When the staggered distance of the coal pillar in the upper and lower sections is small, the coal pillar in the lower section falls within the range of area I:

\[ \theta_1 = \frac{\pi}{4} + \frac{\phi}{2} \]  

(9)

The lower section coal pillar falls in the upper section coal pillar’s shear failure zone and high-stress influence zone; a relatively large force, poor stability, and easy-to-occur shear failures, such as slices, are observed in the lower section coal pillar.

When the staggered distance value of the coal pillar in the upper and lower sections is sufficiently high, the coal pillar in the lower section falls within the range of zone III:

\[ \theta_2 = \frac{\pi}{4} - \frac{\phi}{2} \]  

(10)

The coal pillar in the lower section is almost not affected by the stress of the coal pillar in the upper section, and the coal pillar is stable, but a considerable amount of coal is lost. The staggered distance of the coal pillar falls in the rock shear fracture surface and the passive compressive stress area (zone II). The coal pillar bears most of the roof pressure but avoids the shear failure zone and the high-stress zone. At this time, although the force on the lower section of the coal pillar is greater than that of the zone III, it does not exhibit a high level of plastic deformation and the stability of the coal pillar is good.

This study revealed that the shear fracture angle of the rock strata depends not only on the internal friction angle of rock deformation, but also on the tensile fracture limit \( \sigma_1 \) and rock cohesion of the material under the condition of the isotropic equivalent tension. The shear angle can be expressed as follows\(^{39}\):

\[ \theta = \arctan \left( \frac{2\sigma_1}{c} \sqrt{1 - \frac{c^2}{2\sigma_1^2} - \frac{\sigma_m}{\sigma_1}} \right) \]  

(11)

where \( \sigma_m \) is the average stress, \( \sigma_1 \) is the limit of the tensile fracture, and \( c \) is the cohesion of the rock.

According to the geometric relationship shown in Figure 3, the following can be obtained:

\[ \beta = \frac{\pi}{2} - \theta \]  

(12)

Therefore, the reasonable staggered distance value of the coal pillar in multiseam mining is as follows:
where \( l_{\text{min}} \) is the minimum staggered mining distance value and \( l_{\text{max}} \) is the maximum value.

### 3 | ENGINEERING PRACTICE

The surface of the Xiaobaodang Coal Mine is a loess-hill, blown-sand region with sandy dunes and a simple geological and fragile ecological environment. The mining plan for the panel and the K5 borehole data of working face 122106 are shown in Figure 4. The primary coal seam of the mine has three layers: No. 1, No. 2, and No. 3, which are distributed nearly horizontally. Among them, coal seam No. 1 has an average thickness of 4.00 m and a buried depth of 206-215 m; the bedrock is 176-205 m thick and the soil layer is 10-40 m thick. In the case of coal seam No. 2, the average thickness is 3.00 m and the average buried depth is 236 m. The rock group between No. 1 and No. 2 is composed of siltstone, medium sandstone, and fine sandstone, and the average interval between the layers is 20 m. In the case of coal seam No. 3, the average thickness is 4.00 m and the average buried depth is 255 m; the bottom plate is fine sandstone. The rock group between No. 2 and No. 3 is siltstone and fine sandstone, and the average interval between the layers is 18 m. The floor rock group is fine sandstone and siltstone, with a total thickness of 34 m. The mechanical properties of the main rock are shown in Table 1.

#### 3.1 | Elastic calculation of staggered distance values for multiseam mining

Figures 5 and 6 can be obtained by introducing the data in Table 1 into formula (4), where 0.1 (\( \sigma_x \), \( \sigma_y \), and \( \tau_{xz} \)) correspond to the dashed green line in the figure, and the inverse solution \( x \) can be obtained by introducing the following into formula (5):

The minimum staggered mining distance between coal seam Nos. 1 and 2 is \( l_{\text{min}} = \max\{33 \text{ m}, 22 \text{ m}, 19 \text{ m}\} = 33 \text{ m} \). The minimum staggered mining distance between Nos. 2 and 3 is \( l_{\text{min}} = \max\{31 \text{ m}, 20 \text{ m}, 18 \text{ m}\} = 31 \text{ m} \).

According to the mining plan of panel 122106, the working face width of coal seam Nos. 1, 2, and 3 is 200 m, and the coal pillar width is \( B = 20 \text{ m} \). The working face parameters of coal seam No. 1 are as follows: \( \lambda = 0.2 \),

![Table 1](image)

| Column | Elevation (m) | Thickness (m) | Lithology   |
|--------|--------------|--------------|-------------|
| 1126   | 36           | Fine sand    |
| 1090   | 4            | Red clay     |
| 1086   | 12           | Fine sandstone|
| 1074   | 20           | Medium sandstone|
| 1054   | 8            | Sandy mudstone|
| 1046   | 16           | Fine sandstone|
| 1030   | 12           | Silt stone   |
| 1018   | 30           | Mud stone    |
| 988    | 24           | Coarse sandstone|
| 964    | 20           | Silt stone   |
| 944    | 12           | Fine sandstone|
| 932    | 8            | Sandy mudstone|
| 924    | 10           | Silt stone   |
| 914    | 4            | No.1 coal seam|
| 910    | 8            | Medium sandstone|
| 872    | 8            | Silt stone   |
| 894    | 4            | Fine sandstone|
| 890    | 3            | No.2 coal seam|
| 887    | 6            | Silt stone   |
| 881    | 12           | Fine sandstone|
| 869    | 4            | No.3 coal seam|
| 865    | 24           | Fine sandstone|
| 841    | 10           | Silt stone   |

![Figure 4](image) Plan view of the local panel layout and drill column
φ = 25°, and \( H = 20 \) m. The working face parameters of coal seam No. 2 are as follows: \( \lambda = 0.22 \), \( \phi = 29° \), and \( H = 18 \) m. These parameters are brought into formula (6) to obtain the following:

The maximum staggered distance value between coal seam Nos. 1 and 2 is \( l_{\text{max}} = 45.67 \) m. The maximum staggered distance value between coal seam Nos. 2 and 3 is \( l_{\text{max}} = 45.02 \) m.

Combining the calculation results and calculating using formula (7), we obtain the following:

The reasonable staggered distance value between coal seam Nos. 1 and 2 is \( l = 33-46 \) m.

The reasonable staggered distance value between coal seam Nos. 2 and 3 is \( l = 31-45 \) m.

### 3.2 Calculation of slip line field for multiseam staggered distance

Xiaobaodang Coal Mine is located in Yushen Coalfield and occurrence of multiple coal seams, although the coal seam belongs to medium-deep-buried coal seam, the thickness of coal seam is large, the strength of overburden strata is low, repeated mining of multiple coal seams and other factors, so that the surface subsidence is serious and the surface cracks are more developed. Most of the water-flowing fracture zones lead to the ground, and serious plastic deformation often occurs in overburden strata and coal pillars.\(^{40-45}\) Therefore, the plastic slip line field theory is also suitable for Xiaobaodang Coal Mine.

The change in the internal stress in the width range of the coal pillar should be ignored. The internal friction angle, tensile strength, and shear strength of the interlayer rock layer are taken as the average value of the interlayer rock layer parameters. The parameters in Table 1 are inserted into Equations (9)-(13).

The staggered distance mining parameters of coal seam Nos. 1 and 2 are as follows: \( \phi = 40.5° \), \( \Theta_2 = 24.57° \), \( \sigma_1 = 4.48 \) MPa, \( c = 1.25 \) MPa, \( \sigma_m = 2.53 \) MPa, and \( \Theta = 84.98° \). The staggered distance mining parameters of coal seam Nos. 2 and 3 are as follows: \( \phi = 42° \), \( \Theta_2 = 24° \), \( \sigma_1 = 5.28 \) MPa, \( c = 1.95 \) MPa, \( \sigma_m = 2.53 \) MPa, and \( \Theta = 82.22° \).

The minimum staggered distance between coal seam Nos. 1 and 2 is \( l_{\text{min}} = 27 \) m; for Nos. 2 and 3, the distance is \( l_{\text{min}} = 26 \) m.

### Table 1  Mechanical parameters of main rock

| Lithology     | Thickness (m) | Tensile strength (MPa) | Cohesion (MPa) | Friction (°) | Bulk modulus (GPa) | Shear modulus (GPa) |
|---------------|---------------|------------------------|----------------|--------------|--------------------|--------------------|
| Fine sand     | 36            | 0.12                   | 0.23           | 15           | 0.12               | 0.04               |
| Red clay      | 4             | 1.50                   | 2.00           | 31           | 0.43               | 0.21               |
| Fine sandstone| 12            | 1.14                   | 1.40           | 35           | 4.56               | 0.22               |
| Medium sandstone| 20         | 1.04                   | 1.25           | 40           | 0.68               | 0.36               |
| Sandy mudstone| 8             | 1.40                   | 2.50           | 30           | 0.64               | 0.31               |
| Fine sandstone| 16            | 1.14                   | 1.40           | 35           | 0.46               | 0.22               |
| Silt stone    | 12            | 1.04                   | 1.25           | 34           | 0.68               | 0.36               |
| Mud stone     | 30            | 0.32                   | 1.80           | 38           | 0.91               | 0.85               |
| Coarse sandstone| 24          | 1.30                   | 1.14           | 35           | 0.46               | 0.22               |
| Silt stone    | 20            | 1.04                   | 1.25           | 24           | 0.68               | 0.36               |
| Fine sandstone| 12            | 1.40                   | 2.50           | 30           | 0.64               | 0.31               |
| Sandy mudstone| 8             | 1.14                   | 1.40           | 35           | 0.46               | 0.22               |
| Silt stone    | 10            | 1.14                   | 1.40           | 38           | 0.46               | 0.22               |
| No. 1 coal seam| 4            | 1.40                   | 2.50           | 30           | 0.64               | 0.31               |
| Medium sandstone| 8           | 2.50                   | 0.86           | 44.5         | 1.27               | 0.85               |
| Silt stone    | 8             | 1.14                   | 1.40           | 35           | 0.46               | 0.22               |
| Fine sandstone| 4             | 0.80                   | 1.50           | 42           | 1.00               | 0.99               |
| No. 2 coal seam| 3            | 0.33                   | 1.20           | 37           | 0.61               | 0.33               |
| Silt stone    | 6             | 1.14                   | 1.40           | 41           | 0.46               | 0.22               |
| Fine sandstone| 12            | 1.40                   | 2.50           | 43           | 0.64               | 0.31               |
| No. 3 coal seam| 4            | 0.32                   | 1.10           | 36.5         | 0.59               | 0.29               |
| Fine sandstone| 24            | 0.80                   | 1.50           | 42           | 1.00               | 0.99               |
| Silt stone    | 10            | 1.80                   | 0.54           | 38           | 0.56               | 0.29               |
The maximum staggered distance between coal seam Nos. 1 and 2 is \( l_{\text{max}} = 44.9 \) m; for Nos. 2 and 3, the distance is \( l_{\text{max}} = 40.4 \) m.

Combining the calculation results and calculating using formula (7), we obtain the following:

The reasonable staggered distance between coal seam Nos. 1 and 2 is \( l = 27-45 \) m.

The reasonable staggered distance between coal seam Nos. 2 and 3 is \( l = 26-41 \) m.

The plastic model of staggered distance mining for multi-seam coal is shown in Figure 7.

On the basis of the comparable theoretical analysis and calculation results of our engineering practice, we concluded that the reasonable staggered distance mining calculated by the elastic theory was more accurate than that obtained using the plastic theory, and was more consistent with the engineering background.

### 4 NUMERICAL SIMULATION AND DIFFERENT STAGGERED DISTANCE SCHEME OPTIMIZATION

#### 4.1 Numerical simulation model

In this study, a numerical simulation model was built, keeping under consideration the geological conditions of the Xiaobaodang Coal Mine, which was chosen as the background for this study. To further discuss the distribution of stress and the plastic zone for the multiseam mining schemes, the influences of the different staggered distance mining and filling sequences on surface subsidence, and the stability of the strip filling body were studied using the numerical simulation software FLAC3D. The three-dimensional model was 700 m \( \times \) 500 m \( \times \) 295 m (L \( \times \) W \( \times \) H) in size, and consisted of 383 500 zones and 79 712 nodes, as shown in Figure 8. The Mohr-Coulomb elastic-plastic constitutive relation was used.
to determine the mechanical behavior of the rock strata in the numerical calculation model. The main rock mechanical parameters are listed in Table 1. The main coal seam of the mine had three layers: coal seam Nos. 1, 2, and 3. Each coal seam had an arrangement with left and right working faces, and the downward mining method was adopted. According to the panel 122106 mining plan, a 20-m section of coal pillar was reserved between the same coal working faces, and the model boundary was reserved for 60 m.

A comprehensive analysis of the average distance between the upper and lower coal seams, overburden thickness, rock mechanical parameters, stress transfer angle, and other parameters revealed that the optimal staggered distance minimized the peak stress of the lower coal pillar after mining of the upper coal pillar (in the Mohr-Coulomb elastic-plastic constitutive condition, the stress in the goaf could be effectively transferred downward through the coal pillars). Meanwhile, the lower coal working face and pillar could effectively avoid the staggered distance between the upper and the lower coal pillars in the stress concentration area of the upper coal seam.

4.2 | Numerical simulation of double-seam and different staggered distance scheme optimization

4.2.1 | Numerical simulation scheme of double-seam mining

According to the calculation results of elasticity and slip line field theory, the staggered mining schemes set for the double-seam (coal seam Nos. 1 and 2) were 0 m, 20 m, 40 m, 60 m, and 80 m, respectively. The parameters of the numerical simulation scheme are listed in Table 2.

4.2.2 | Analysis and optimization of double-seam staggered distance scheme

The distribution of the maximum principal stress of the staggered distance of the double-seam was obtained as shown in Figure 9, where the transparent area in the figure represents the goaf, while the coal pillar is the area between the goaf in the same layer.

When the staggered distance in the double-seam mining was 0 m, the coal pillar of No. 2 coal seam was located in the pressurized area formed by coal seam No. 1; additionally, there was a nearly connected principal stress influence area between the coal pillars. The coal pillar of coal seam No. 2 was seriously damaged, and roadway support was difficult. The peak stress in the affected zone of the maximum principal stress between the staggered coal pillars was 10.09 MPa, as shown in Figure 9A.

With the increase in the staggered distance of the coal pillar, the influence zone of the principal stress between the upper and the lower coal pillars gradually separated. Moreover, the concentration area of the central principal stress of the coal pillar decreased. When the staggered distance value was 40 m, the stress transition in the stress concentration zone between the staggered coal pillars was uniform. The influence area of the principal stress was further reduced, with the peak
value of the maximum principal stress falling to 5.00 MPa, as shown in Figure 9B.

With further increase in the staggered distance, the left working face of coal seam No. 2 gradually entered the goaf compaction area of the right face of coal seam No. 1. Moreover, the coal pillar of coal seam No. 2 was affected by the stress of the boundary pillar of coal seam No. 1. In the case of coal seam No. 2, the right working face was in the stress release zone of coal seam No. 1, and the stress was superimposed. The stability of the pillar gradually worsened.

As a result of the support provided by the coal pillar to the coal seam roof, as well as the influence of the unloading and collapse of the goaf, the overburden stress of the coal seam was transferred to the coal pillar. Therefore, the central stress value of the coal pillar was observed to be the highest during staggered distance mining. The $\sigma_{zz}$ and $Z$ displacement in the width range of ±40 m at the center of the coal pillar in coal seam No. 2 center was extracted, in order to analyze the stability of the coal pillars.

As shown in Figure 10A, the $\sigma_{zz}$ curve of the coal pillar in coal seam No. 2 presents a “peak” distribution. The maximum principal stress peak appeared at the center of the coal pillar, and the stress of the edge of the staggered coal pillar dropped considerably. The principal stress in the width range was 3-6 times that of the pressure relief area on both sides, and the two sides of the coal pillar became easily breakable and developed cracks. When the staggered distance of the coal seam was 0 m, 20 m, 40 m, 60 m, and 80 m, the peak value of the main stress of the coal pillar was 11.29 MPa, 9.10 MPa, 7.83 MPa, 8.41 MPa, and 8.77 MPa, respectively.

In double-seam mining, as a result of the unloading effect of the upper coal (coal seam No. 1) mining, the center range of the lower coal (coal seam No. 2) pillar ($\sigma_{zz}$) was significantly lower than that of the upper coal pillar ($\sigma_{zz}$). With the increase in the staggered distance mining, the peak stress of $\sigma_{zz}$ experienced “decrease and then increase,” as shown in Figure 11.

The $Z$ displacement curve of the center range of the coal pillar with different staggered distance values presented a “Л”-shaped distribution. The subsidence value at the center of the coal pillar was the smallest, and the subsidence value outside the width range of the coal pillar gradually increased. Moreover, the subsidence value in the width range of the coal pillar was less than 1/4-1/2 of the goaf on both sides. When the staggered distance values of the coal seam were 0 m, 20 m, 40 m, 60 m, and 80 m, the subsidence values of the coal pillar center were 0.125 m, 0.085 m, 0.055 m, 0.069 m, and 0.099 m, respectively. The maximum subsidence value also showed a trend of “decrease then increase,” as shown in Figure 10B.

By extracting the monitoring point data of the numerical simulation, we observed that the overall subsidence curve of coal seam Nos. 1 and 2 showed a “W” distribution, as shown in Figure 12. The maximum value of the surface subsidence was in the middle of each working face, and the minimum subsidence was directly above the middle coal pillar. Moreover, the average subsidence coefficient of coal seam No. 1 was 0.33. In the case of coal seam No. 2, staggered mining, when the staggered distance value was 0 m, the maximum value of the surface subsidence was 1.81 m and the average subsidence coefficient value was 0.27. The surface subsidence fluctuation and the disturbance of the left and right goaf of

| Scheme | No. 1 coal seam height (m) | No. 2 coal seam height (m) | Average spacing for coal seam Nos. 1 and 2 (m) | Staggered distance (m) | Coal pillar width (m) | Working face length (m) | Working face width (m) |
|--------|--------------------------|--------------------------|---------------------------------------------|----------------------|---------------------|-----------------------|-----------------------|
| One    | 4.00                     | 3.00                     | 20.00                                       | 0                    | 20                  | 380                   | 200                   |
| Two    | 4.00                     | 3.00                     | 20.00                                       | 20                   | 20                  | 380                   | 200                   |
| Three  | 4.00                     | 3.00                     | 20.00                                       | 40                   | 20                  | 380                   | 200                   |
| Four   | 4.00                     | 3.00                     | 20.00                                       | 60                   | 20                  | 380                   | 200                   |
| Five   | 4.00                     | 3.00                     | 20.00                                       | 80                   | 20                  | 380                   | 200                   |

**TABLE 2** Numerical simulation scheme

**FIGURE 9** Maximum principal stress curve of different staggered distance values for double-seam mining
the coal pillar were the largest, and the shear stress on both sides of the coal pillar was concentrated. With the increase in staggered distance, the gradient (deflection) of the surface subsidence curve gradually decreased. When the staggered distance value of the coal pillar was 40 m, the surface subsidence value was the smallest (1.66 m) and the average subsidence coefficient was 0.24. The subsidence curve was gentle, which could effectively reduce the degree of surface damage. At the same time, when the staggered distance value of the coal pillars was more than 40 m, the gradient (deflection) of the surface subsidence curve increased gradually, and the subsidence curve became steeper. A comprehensive comparison of the central stress distribution and the peak stress of the coal pillar, the cloud chart of the principal stress, and the curve of the surface subsidence revealed the presence of a consistent optimal state; that is, the optimal mining staggered distance value was found to be 40 m.

According to the results, when the staggered distance value was 40 m, the minimum value of the stress peak appeared at the center of the coal pillar, the corresponding subsidence value of the coal pillar center was the minimum, and the surface subsidence curve was the most gentle. In this case, the coal pillar was the safest, which was the optimal staggered distance value for double-seam coal mining.

4.3 | Numerical simulation of multiseam mining and different staggered distance optimization

4.3.1 | Numerical simulation schemes of multiseam mining

According to the theoretical calculation results of elasticity and slip line field and the simulation results of Section 4.2 of double-seam coal mining, the simulation scheme of multiseam mining (Nos. 1, 2, and 3 coal seams) was as follows: When the optimal staggered distance values (40 m) of coal seam Nos. 1 and 2 were kept unchanged, the staggered distance numerical simulation scheme of coal seams of Nos. 3 and 2 is shown in Table 3.

4.3.2 | Analysis and optimization of staggered distance multiseam mining scheme

By simulating staggered distance multiseam mining, we obtained the distribution of the maximum principal stress, as shown in Figure 13, where the transparent area represents the goaf and the coal pillar is the area between the goaf in the same layer.

In staggered distance multiseam mining, the optimal staggered distance values of coal seam Nos. 1 and 2 were kept unchanged (40 m). When the staggered distance value between coal seam Nos. 3 and 2 was 0 m, No. 3 coal seam pillar was within the pressurized zone formed by the stress transmission of coal seam Nos. 1 and 2. There were almost connected principal stress-affected zones between the staggered coal pillars, the coal pillars were severely damaged, and roadway support was difficult. The peak stress in the effect zone between the maximum principal stress between the staggered coal pillars was 8.22 MPa, as shown in Figure 13A. Compared with Figure 9A, the stress of the coal pillar in the lower section was reduced compared with that in double-seam mining, indicating that multiseam mining can effectively disperse stress concentration.
With an increase in the staggered distance value of the coal pillar, the influence zone of the principal stress between the upper and the lower coal pillars gradually separated. Moreover, the concentration area of the central principal stress of the coal pillar decreased. When the staggered distance was 40 m, the stress transition in the stress concentration zone between the staggered coal pillars was uniform. The influence area of the principal stress between the staggered coal pillars was further reduced, and the stress peak value was reduced from 4.00 MPa to 1.25 MPa, as shown in Figure 13B.

With further increase in staggered distance value, the left working face of coal seam No. 3 gradually entered the goaf compaction area of the right working face of No. 2; the coal pillar of No. 3 was considerably affected by the stress of the boundary pillar of No. 2. As No. 2 was affected by No. 1, the right working face of No. 3 was located within the stress release zone of Nos. 1 and 2, and the stress was superimposed.

As a result of the comprehensive influence of stress redistribution of multiseam mining and goaf unloading, the overburden stress of coal seam Nos. 2 and 3 was dispersed and transferred to each coal pillar of the layer. In the case of staggered distance mining, the stress distribution at the center of the coal pillar was consistent with the stress distribution of double-seam mining. The $\sigma_{zz}$ and Z displacement in the width range of ±40 m at the center of the pillars in coal seam Nos. 2 and 3 were extracted to analyze coal pillar stability.
The $\sigma_{zz}$ curves showed a “peak” distribution, the maximum principal stress peak appeared at the center of the coal pillar, and the peak stress of $\sigma_{zz}$ changed from large to small and then increased to large, as shown in Figure 16. When the staggered distance values of multiseam mining were 0 m, 20 m, 40 m, 60 m, and 80 m, the stress peak of the coal pillar in coal seam No. 2 was 4.98 MPa, 3.67 MPa, 2.89 MPa, 3.10 MPa, and 3.44 MPa, respectively, which was smaller than that of multiseam mining in the case of coal seam No. 2, but larger than the value of double-seam mining in coal seam No. 2 (Figure 14B). The central subsidence value of the coal pillar in coal seam No. 3 was 0.214 m, 0.194 m, 0.165 m, 0.184 m, and 0.203 m, respectively, which was twice as much as the value of double-seam mining (Figure 14B). The central subsidence value of the coal pillar in coal seam No. 3 was 0.214 m, 0.194 m, 0.165 m, 0.184 m, and 0.203 m, respectively, which was smaller than that of multiseam mining in the case of coal seam No. 2, but larger than the value of double-seam mining in coal seam No. 2 (Figure 15B).

The multiseam staggered distance mining surface subsidence curve (Figure 17) showed a “W” shape, the maximum value of surface subsidence was in the middle of each working face, and the minimum subsidence was directly above the middle coal pillar. The average subsidence coefficient of coal seam No. 1 was 0.29, and the average subsidence coefficient of coal seam No. 2 was 0.23. When the staggered distance value for multiseam mining was 0 m, the maximum surface subsidence was 2.24 m, the subsidence coefficient was 0.22, the surface subsidence in the middle of the goaf was the highest; additionally, the disturbance on both sides of the coal pillar was the highest.

With the increase in the staggered distance value, the gradient (deflection) of the surface subsidence curve gradually decreased. When the staggered distance value of the coal pillar was 40 m, the maximum subsidence value of the surface was 1.92 m, and the subsidence coefficient was 0.19. Additionally, the subsidence curve was smooth, which could effectively slow the degree of surface damage. At the same time, when the staggered distance value of the coal pillar was 60 m and 80 m, the subsidence coefficient was 0.20 and 0.21, respectively, and consequently, the subsidence curve became steeper. Compared with the subsidence curve of double-seam mining (Figure 12), the staggered distance mining of multiseam could effectively slow down surface subsidence and reduce the development of surface cracks.

A comprehensive comparison of the overburden stress distribution and stress peak value, $Z$ displacement of the coal pillar center, and the surface subsidence curve showed a consistent optimal state among them. Thus, we concluded that the optimal staggered distance value of multiseam mining was obtained when the optimal staggered distance of coal seam Nos. 1 and 2 was 40 m, the optimal staggered distance values of coal seam Nos. 2 and 3 was 40 m, and the most unfavorable staggered distance value was 0 m.

### TABLE 3 Numerical simulation scheme

| Scheme | No. 2 coal seam height (m) | No. 3 coal seam height (m) | Average spacing for coal seam No. 2 and 3 (m) | Staggered distance (m) | Coal pillar (m) | Working face length (m) | Working face width (m) |
|--------|---------------------------|---------------------------|---------------------------------|------------------------|-----------------|------------------------|------------------------|
| One    | 3.00                      | 4.00                      | 18.00                           | 0                      | 20              | 380                    | 200                    |
| Two    | 3.00                      | 4.00                      | 18.00                           | 20                     | 20              | 380                    | 200                    |
| Three  | 3.00                      | 4.00                      | 18.00                           | 40                     | 20              | 380                    | 200                    |
| Four   | 3.00                      | 4.00                      | 18.00                           | 60                     | 20              | 380                    | 200                    |
| Five   | 3.00                      | 4.00                      | 18.00                           | 80                     | 20              | 380                    | 200                    |

**FIGURE 13** Maximum principal stress curve of different staggered distance values for multiseam mining

The $\sigma_{zz}$ curves showed a “peak” distribution, the maximum principal stress peak appeared at the center of the coal pillar, and the peak stress of $\sigma_{zz}$ changed from large to small and then increased to large, as shown in Figure 16. When the staggered distance values of multiseam mining were 0 m, 20 m, 40 m, 60 m, and 80 m, the stress peak of the coal pillar in coal seam No. 2 was 4.98 MPa, 3.67 MPa, 2.89 MPa, 3.10 MPa, and 3.44 MPa, respectively, which was 0.2-0.7 times the stress peak of the corresponding values of double-seam mining, as shown in Figure 14A. The stress peaks of the coal pillar of coal seam No. 3 were 7.39 MPa, 6.17 MPa, 4.55 MPa, 4.94 MPa, and 5.27 MPa, respectively, as shown in Figure 15A.

With the change in the staggered distance value of multiseam mining, the $Z$ displacement curve of the coal pillar displayed the same change law as double-seam mining. When the staggered distance was 0 m, 20 m, 40 m, 60 m, and 80 m, the central subsidence value of the coal pillar in coal seam No. 2 was 0.251 m, 0.211 m, 0.182 m, 0.233 m, and 0.247 m, respectively, which was twice as much as the value of double-seam mining (Figure 14B). The central subsidence value of the coal pillar in coal seam No. 3 was 0.214 m, 0.194 m, 0.165 m, 0.184 m, and 0.203 m, respectively, which was smaller than that of multiseam mining in the case of coal seam No. 2, but larger than the value of double-seam mining in coal seam No. 2 (Figure 15B).
5 | ANALYSIS AND DISCUSSION

5.1 | Comparative discussion on multiseam mining: optimal and most unfavorable staggered distance schemes

In order to compare the influence of the optimal and the most unfavorable staggered distance schemes in multiseam mining on ground and overburden strata, a two-dimensional model framework of 2000 mm in length, 200 mm in width, and 1210 mm in height was selected to build two physical models based on similarity theory. The comparative experimental results of the two models are shown in Figures 18 and 19.

Figure 18A, B shows the range of the caved zone and the morphology of the fractured water-conducting zone in the overburden strata of the optimal and the most unfavorable staggered distance scheme. According to Figure 18A, the overburden strata was severely damaged; additionally, there were four cracks in the ground. Vertical displacement can be clearly seen on the surface, and the height of the caved zone across the left and right working faces was 210 m and 186 m, respectively. Finally, the interior of the caved zone was relatively broken, the range of the fractured water-conducting zone was large, and the development width of the water diversion cracks was wide. In Figure 18B, when mining using the optimal staggered distance scheme, the overburden strata was slightly damaged, there were four cracks in the ground, vertical displacement was no longer clearly visible on the surface, and the height of the caved zone across the left and right working faces was 210 m and 186 m, respectively. Finally, the interior of the caved zone was relatively broken, the range of the fractured water-conducting zone was large, and the development width of the water diversion cracks was wide.
surface, and there was a uniform subsidence of overburden strata. The height of the caved zone across the left and right working faces was 195 m and 135 m, respectively, and the interior of the caved zone was more complete, the range of fractured water-conducting zone was smaller, and the development width of fractured water-conducting was also relatively small.

Figure 19A,B shows the shape and position of the surface cracks in the optimal and the most unfavorable staggered distance schemes. The results showed that in the optimal scheme, the maximum vertical displacement of surface cracks was 0.2 mm, and the maximum width was 1.5 mm (as shown in Figure 19A). In the most unfavorable staggered distance scheme, the maximum vertical displacement of the surface cracks was 4 mm, which was 20 times that of the optimal scheme; the maximum width of the surface cracks was 2.5 mm, which was 1.67 times that of the optimal scheme (as shown in Figure 19B).

The height of the fractured water-conducting zone and the width of the surface cracks are important in addressing the problems of water retention and loss reduction. Physical model tests, performed by making use of a similar material, illustrate that the optimal staggered distance scheme can effectively slow down the expansion of surface cracks, reduce the damage to overburden strata caused by coal mining, and effectively shorten the development height of the fractured water-conducting zone. By optimizing the staggered distance mining scheme, we were able to effectively solve the problems of water retention and loss reduction.
5.2 | Comparative discussion on staggered distance double-seam and multiseam mining

Based on the law of stress transfer in the coal pillar and the overburden strata, the mechanical model of staggered distance double-seam and multiseam mining was established using the elastic and plastic slip line field theory, and the range of the reasonable staggered distance was calculated using an engineering practice. The stress distribution of the coal pillar, central subsidence value of the coal pillar, and the surface subsidence curve under double-seam and multiseam staggered distance mining were obtained using the numerical simulation method. Comparison of the numerical simulation and theoretical calculation results revealed that the reasonable staggered distance value calculated by the elastic theory was more accurate than the value calculated using the plastic theory, and was more consistent with the numerical simulation results. The rationality of the theoretical calculation was verified with numerical simulation. The above research work is innovative and has good application value.

Figures 10 and 14 show the stress and displacement of the center of the coal pillar during double-seam and multiseam staggered distance mining. Through comparison and analysis, we found that the peak stress of the coal pillar in coal seam No. 2, during multiseam mining, was only 0.2-0.7 times that of double-seam mining; additionally, the central subsidence value of the coal pillar in coal seam No. 2 was approximately twice as much as that of double-seam mining. Figures 12 and 17 show the surface subsidence curve of double-seam mining and multiseam mining. During optimal double-seam staggered distance mining, the subsidence coefficient of coal seam Nos. 1 and 2 was 0.33 and 0.24, while in optimal multiseam staggered distance mining, the subsidence coefficients of coal seam Nos. 1, 2, and 3 were 0.29, 0.23, and 0.19. By optimizing the staggered distance mining scheme, we found that surface subsidence could be effectively reduced, the coal pillar stress concentration effect could be effectively avoided, and the development of surface cracks could be slowed down.

In addition to theoretical analysis, physical and numerical simulation methods were used in this study. Field detection techniques could also potentially be used to analyze and optimize multiseam mining and roadway layout schemes. However, this method is costly and time-intensive and has a large degree of data interference; additionally, the results largely depend on the accuracy and proficiency of manual operation.

5.3 | There are still some deficiencies in this study

1. The stress and deformation of the overburden strata in the coal mining face is affected by a number of factors, such as mining width, mining length, mining height, overburden thickness, and number of key strata. In addition, in multiseam mining, the overburden strata are repeatedly disturbed, and the stress release and redistribution are more complex and changeable. In this paper, we only discussed the multiseam staggered distance mining under specific mining conditions, without taking into consideration other potential influencing factors. Future research should focus on optimization of multiseam staggered mining under additional factors such as these factors.

2. As a result of the large geological coal mining model, in the process of staggered distance mining, the staggered distance multiseam scheme was only considered by the multiple increases in the width of the section coal pillar, and the gradient of the staggered distance scheme was not subdivided.

3. Using FLAC3D, we were better able to simulate changes in the stress of the surrounding and overlying rock displacement during the process of coal seam mining, but we were
unable to clearly show the development of cracks in the overlying rock or the collapse of the roof in the goaf. At a later stage, other numerical simulation software will be introduced for coupling research.21,33

6 | CONCLUSIONS

To analyze the reasonable staggered distance values of the coal pillars during double-seam and multiseam mining, the stress transfer model of staggered distance multiseam mining was established. Numerical simulation was used to optimize the staggered distance mining scheme, along with theoretical analysis and engineering practice. The primary conclusions of this study were as follows:

1. Considering the comprehensive influence of coal pillar stress transmission and goaf compaction, we devised a formula for a reasonable staggered distance range for double-seam mining, using the elastic theory. Combined with theoretical analysis and engineering practice, the reasonable staggered distance mining between coal seam Nos. 1 and 2 was \( l = 33-46 \) m; between Nos. 2 and 3, \( l = 31-45 \) m. According to the plastic slip line field theory, the reasonable staggered distance mining of coal seam Nos. 1 and 2 was \( l = 27-45 \) m; Nos. 2 and 3, \( l = 26-41 \) m. Additionally, the reasonable staggered distance mining value calculated using the elastic theory was more accurate than the value obtained using the plastic theory.

2. (a) The \( \sigma_{zz} \) curve in the influence range of the staggered coal pillar showed a “peak” distribution, the \( Z \) displacement curve in the central range of the coal pillar showed a “J” distribution, and the surface subsidence curves showed a “W” shape. (b) The peak value of \( \sigma_{zz} \) and the minimum value of \( Z \) displacement appeared at the center of the coal pillar. (c) The maximum surface subsidence was in the middle of each working face, and the minimum subsidence was at the center of the coal pillar. (d) With an increase in the staggered distance, the distribution characteristics of the maximum principal stress, the \( Z \) displacement curve of the coal pillar, and the surface subsidence curves all experienced “a decrease and then increase.”

3. (a) In staggered distance double-seam mining, the optimal staggered distance value was 40 m and the most unfavorable staggered distance value was 0 m. For multiseam
mining, when the optimal staggered distance value of coal seam Nos. 1 and 2 was unchanged, the optimal staggered distance value for coal seam Nos. 2 and 3 was 40 m and the most unfavorable staggered distance value was 0 m. Meanwhile, the $\sigma_{zz}$ peak value of the pillar of coal seam No. 2 was 0.2-0.7 times the peak stress of observed during double-seam mining. By optimizing the staggered distance mining scheme, we could effectively avoid the coal pillar stress concentration. (b) The optimal staggered distance for double-seam mining had corresponding sinking coefficients of 0.33 and 0.24. For multiseam mining, the subsidence coefficients were 0.29, 0.23, and 0.19. By optimizing the staggered distance mining scheme, we observed that surface subsidence resulting from multiseam mining could be effectively reduced, coal pillar stability could be maintained, and the development of surface cracks could be slowed down.

ACKNOWLEDGMENTS
This work is supported by Key Laboratory of Exploration and Comprehensive Utilization of Mineral Resources, the National Natural Science Foundation of China (Nos. 41272388 and 40572155). The authors also thank the editor and anonymous reviewers very much for their valuable advice. All the authors have agreed to the given listing of authors.

ORCID
Mingjiao Lu https://orcid.org/0000-0002-1564-7742

REFERENCES
1. Ghabraie B, Ren G, Zhang X, Smith J. Physical modelling of subsidence from sequential extraction of partially overlapping longwall panels and study of substrata movement characteristics. Int J Coal Geol. 2015;140:71-83.
2. Nicieza CG, Álvarez Fernández M, Menéndez Díaz A, Álvarez Vigil A. The new three-dimensional subsidence influence function denoted by nkg. Int J Rock Mech Min Sci. 2005;42(3):372-387.
3. Can E, Kuscu Ş, Mekik C. Determination of underground mining induced displacements using GPS observations in Zonguldak Kozlu Hard Coal Basin. Int J Coal Geol. 2012;89:62-69.
4. Dawei Z, Kan W, Zhihui B, et al. Formation and development mechanism of ground crack caused by coal mining: effects of overlying key strata. Bull Eng Geol Environ. 2017;76(2):1025-1044.
5. Huang Y, Tian F, Wang Y, Wang M, Hu Z. Effect of coal mining on vegetation disturbance and associated carbon loss. Environ Earth Sci. 2014;73(5):2329-2342.
6. Chi M, Zhang D, Fan G, Zhang W, Liu H. Prediction of water resource carrying capacity by the analytic hierarchy process-fuzzy discrimination method in a mining area. Ecol Indic. 2019;96:647-655.
7. Zhang D, Fan G, Liu Y, Ma L. Field trials of aquifer protection in longwall mining of shallow coal seams in China. Int J Rock Mech Min Sci. 2010;47(6):908-914.
8. Zhang J, Shen B. Coal mining under aquifers in China: a case study. Int J Rock Mech Min Sci. 2004;41(4):629-639.
9. Zhu D, Song X, Li H, Liu Z, Wang C, Huo Y. Cooperative load-bearing characteristics of a pillar group and a gob pile in partially caved areas at shallow depth. Energy Sci Eng. 2019;8(1):89-103.
10. Wen J, Cheng W, Chen L, Shi S, Wen Z. A study of the dynamic movement rule of overlying strata combinations using a short-wall continuous mining and full-caving method. Energy Sci Eng. 2019;7(6):2984-3004.
11. Tao M, Ji X, Xm L, et al. Experimental study on the evolutional trend of pore structures and fractal dimension of low-rank coal rich clay subjected to a coupled thermo-hydro-mechanical chemical environment. Energy. 2020;203:117838.
12. Yang W, Lin B, Qu Y, et al. Stress evolution with time and space during mining of a coal seam. Int J Rock Mech Min Sci. 2011;48(7):1145-1152.
13. Zhang Y, Zhang Z, Xue S, et al. Stability analysis of a typical landslide mass in the Three Gorges Reservoir under varying reservoir water levels. Environ Earth Sci. 2020;79(1):1-14.
14. Ren G, Li G, Kulessa M. Application of a generalised influence function method for subsidence prediction in multi-seam longwall extraction. Geotech Geol Eng. 2014;32(4):1123-1131.
15. Yan H, Weng M-Y, Feng R-M, et al. Layout and support design of a coal roadway in ultra-close multiple-seams. J Cent South Univ. 2015;22(11):4385-4395.
16. Tulu IB, Esterhuizen GS, Klemetti T, et al. A case study of multi-seam coal mine entry stability analysis with strength reduction method. Int J Min Sci Technol. 2016;26(2):193-198.
17. Xie J, Xu J, Wang F, et al. Deformation effect of lateral roof roadway in close coal seams after repeated mining. Int J Min Sci Technol. 2014;24(5):597-601.
18. Chenglin T, Xuelsing Y, Haitao S, et al. Experimental study on the overburden movement and stress evolution in multi-seam mining with residual pillars. Energy Sci Eng. 2019;7(6):3095-3110.
19. Ghabraie B, Ren G, Smith JV. Characterising the multi-seam subsidence due to varying mining configuration insights from physical modelling. Int J Rock Mech Min Sci. 2017;93:269-279.
20. Ghabraiea B, Rena G, Smitha J, et al. Application of 3D laser scanner, optical transducers and digital image processing techniques in physical modelling of mining-related strata movement. Int J Rock Mech Min Sci. 2015;80:219-230.
21. Adhihary D, Khanal M, Jayasundara C, et al. Deficiencies in 2D simulation of multi-seam longwall mining. Rock Mech Rock Eng. 2015;49(6):2181-2185.
22. Ghabraie B, Ghabraie K, Ren G, et al. Numerical modelling of multistage caving processes: insights from multi-seam longwall mining-induced subsidence. Int J Numer Anal Meth Geomech. 2017;41(7):959-975.
23. Ghabraiea B, Ren G, Barbato J, et al. A predictive methodology for multi-seam mining induced subsidence. Int J Rock Mech Min Sci. 2017;93:280-294.
24. Suchowierska Iwanec AM, Carter JP, Hambleton JP. Geomechanics of subsidence above single and multi-seam coal mining. J Rock Mech Geotech Eng. 2016;8(3):304-313.
25. Sepehri M, Apel DB, Hall RA. Prediction of mining-induced surface subsidence and ground movements at a Canadian diamond mine using an elastoplastic finite element model. Int J Rock Mech Min Sci. 2017;100:73-82.
26. Yang X, Wen G, Dai L, et al. Ground subsidence and surface cracks evolution from shallow-buried close-distance multi-seam
mining: a case study in Bulianta Coal Mine. *Rock Mech Rock Eng*. 2019;52(8):2835-2852.

27. Suchowerskan AM, Merifield RS, Carter JP. Vertical stress changes in multi-seam mining under supercritical longwall panels. *Int J Rock Mech Min Sci*. 2013;61:306-320.

28. Khanal M, Adhikary D, Jayasundara C, et al. Numerical study of mine site specific multiseam mining and its impact on surface subsidence and chain pillar stress. *Geotech Geol Eng*. 2015;34(1):217-235.

29. Karl Zipf R. Failure mechanics of multiple seam mining interactions. In: 24th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University; 2005:93-106.

30. Kumar A, Waclawik P, Singh R, et al. Performance of a coal pillar at deeper cover: field and simulation studies. *Int J Rock Mech Min Sci*. 2019;113:322-332.

31. Zhang M, Shimada H, Sasaoka T, et al. Evolution and effect of the stress concentration and rock failure in the deep multi-seam coal mining. *Environ Earth Sci*. 2013;72(3):629-643.

32. Shang H, Ning J, Hu S, et al. Field and numerical investigations of gateroad system failure under an irregular residual coal pillar in close-distance coal seams. *Energy Sci Eng*. 2019;7(6):2720-2740.

33. Zhiheng C, Zhenhua O, Quanle Z, et al. Characteristics of fracture field in different stress zones during multi-seam mining: quantification based on theoretical analysis and BBM-DEM accurate simulation method. *Energy Sci Eng*. 2020;8(5):1620–1633.

34. Qingxiang H, Jian C, Junwu D. Research on three-field evolution and rational coal pillar staggered distance in shallow buried closely spaced multi-seam mining. *J China Coal Soc*. 2019;44(3):681-689.

35. He W, He F, Zhao Y. Field and simulation study of the rational coal pillar width in extra-thick coal seams. *Energy Sci Eng*. 2019;8(3):627-646.

36. Zhu Z, Zhang H, Nemcik J, et al. Overburden movement characteristics of top-coal caving mining in multi-seam areas. *Q J Eng Geol Hydrogeol*. 2018;51(2):276-286.

37. Wu G, Fang X, Bai H, et al. Optimization of roadway layout in ultra-close coal seams: a case study. *PLoS One*. 2018;13(11):e0207447.

38. Qiu L, Song D, He X, et al. Multifractal of electromagnetic waveform and spectrum about coal rock samples subjected to uniaxial compression. *Fractals*. 2020;28(4):2050061.

39. Hegang Q, Jianhao Y. Rationality and comprehensive unloading technology of deep high stress section coal pillars. *J China Coal Soc*. 2018;43(12):3257-3264.

40. Huang Q, Cao J. Research on coal pillar malposition distance based on coupling control of three-field in shallow buried closely spaced multi-seam mining, China. *Energies*. 2019;12(3):462.

41. Jiazhao L, Jibing Z, Junling H, et al. Multiple disturbance instability mechanism of dynamic pressure roadway and mining sequence optimization. *J Min Saf Eng*. 2015;32(3):439-445.

42. Liqiang M, Dongsheng Z, Zhiyuan J. Theories and methods of efficiency water conservation mining in short-distance coal seams. *J China Coal Soc*. 2019;44(3):727-738.

43. Yanfang R, Yu N, Qingxin Q. Physical analogous simulation on the characteristics of overburden breakage at shallow longwall coalface. *J China Coal Soc*. 2013;38(1):61-65.

44. Wang J, Ning J-G, Tan Y-L, et al. Deformation and failure laws of roadway surrounding rock and support optimization during shallow-buried multi-seam mining. *Geomat Nat Hazards Risk*. 2020;11(1):191-211.

45. Shen W, Dou L-M, He H, et al. Rock burst assessment in multi-seam mining: a case study. *Arabian J. Geosci*. 2017;10(8):1-11.

46. Zhang Z, Deng M, Wang X, et al. Field and numerical investigations on the lower coal seam entry failure analysis under the remnant pillar. *Eng Fail Anal* 2020;115:104638.

47. Miao X, Cui X, Wang JA, et al. The height of fractured water-conducting zone in undermined rock strata. *Eng Geol*. 2011;120(1-4):32-39.

How to cite this article: Sun X, Lu M, Li C. Optimization of staggered distance of coal pillars in multiseam mining: Theoretical analysis and numerical simulation. *Energy Sci Eng*. 2021;9:357–374. [https://doi.org/10.1002/ese3.824](https://doi.org/10.1002/ese3.824)