INTRODUCTION

Among the energy resources available to mankind, coal is one of the most important as it is abundant in many parts of the world and provides a stable supply.\(^1\) According to statistics from British Petroleum, the proven deep-Earth coal reserves are twice those of petroleum and thrice those of natural gas.\(^2\) In terms of the power generated, the amount of electricity produced using coal is 2.4 times greater than hydropower, 8 times greater than wind power, and 17 times greater than solar power.\(^2\) The generation of wind and solar power requires vast open space while the generation of hydropower is costly,
usually requiring a long construction period, and is known to adversely affect local water resources and climate.\textsuperscript{3,4} As coal mining occurs underground, it avoids many of the limitations of wind power, solar power, and hydropower. As the global energy demand increases, fossil fuel consumption has increased and numerous studies predict that the oil, coal, and natural gas reserves will be depleted in approximately 35, 107, and 37 years, respectively.\textsuperscript{1} Thus, deep-Earth coal resources have enormous exploitation potential and utilization value.

However, the drawbacks and limitations of current technologies, as well as the ecological effects of coal and its derivatives, have resulted in the growth of demands to abandon coal mining worldwide. Despite this, problems have occurred when some countries have switched from coal to clean energy sources, such as hydropower, wind power, and solar power, for electricity generation. In particular, the security of the national grid can be compromised, which may affect the daily lives and social development of a country’s inhabitants. For example, Germany depends significantly on intermittent solar and wind energy; however, for 3 days in June 2019, environmental factors were such that the electricity grid nearly blacked out and short-term electricity imports from neighboring countries were required to stabilize their supply.\textsuperscript{5} Australia and the United Kingdom have faced similar energy supply problems. The intermittent nature of renewable energy has a considerable effect on energy supply security.\textsuperscript{6,7}

The demand for coal abandonment is driven by the shortage of theoretical and technical breakthroughs required to reduce the negative consequences of coal exploitation and utilization, for example, damage to geological formations, surface subsidence, equipment damage, human casualties, damage to the surface and ecological environments during mining,\textsuperscript{8-16} and the emission of greenhouse gases during its utilization.\textsuperscript{17-19} Despite these consequences, coal is still the dominant energy source used for electricity generation and primary energy consumption in many countries, as listed in Table 1. The demand for coal is likely to remain stable for an extended period, as its use is extremely high in developing countries, which are rich in coal reserves, but poor in oil and natural gas, as well as where the per-capita energy consumption is much lower than in developed countries.\textsuperscript{20,21}

Regarding the geological side effects, underground coal excavation causes the transfer and concentration of stress that generates mining-induced stress fields around the mining site.\textsuperscript{22} The concentration of high stresses results in the deformation and failure of the surrounding rock, which may trigger violent rock bursts, especially if the point of peak stress is near roadways or coalfaces.\textsuperscript{23-25} Another concern is that, with the growth of coal consumption, mining depths are increasing every year.\textsuperscript{26,27} The deep rock masses surrounding coal mines are affected by high in situ stress, high pore pressure, high temperature, and mining disturbances over extended periods of time, which may lead to major disasters in deep mining operations. Furthermore, underground mining can induce earthquakes and mining-induced seismic activity increases with the depth of a mine.\textsuperscript{28-33} This could result in damage to buildings and infrastructure or cause natural hazards, such as landslides and mudslides, any of which may cause fatalities and significant economic losses.\textsuperscript{34,35}

As traditional mining

\begin{table}
\centering
\caption{Population, primary energy consumption, and electricity generation of major global coal consumers}
\begin{tabular}{|l|c|c|c|c|c|c|c|}
\hline
\textbf{Country} & \textbf{Population (million)} & \textbf{Total (Mtons)} & \textbf{Per caption (Gj/s)} & \textbf{Contribution of coal (Mtons)} & \textbf{Percentage of coal (%)} & \textbf{Total (TWh)} & \textbf{Contribution of coal (TWh)} & \textbf{Percentage of coal (%)} \\
\hline
China & 1389.62 & 3273.5 & 96.9 & 1906.7 & 58.2 & 7111.8 & 4732.4 & 66.5 \\
India & 1311.56 & 809.2 & 25.0 & 452.2 & 55.9 & 1561.1 & 1176.3 & 75.4 \\
US & 331.88 & 2300.6 & 294.8 & 317.0 & 13.8 & 4460.8 & 1245.8 & 27.9 \\
Indonesia & 264.94 & 215.4 & 29.1 & 61.6 & 33.2 & 267.3 & 156.4 & 58.5 \\
Russia & 141.94 & 720.7 & 209.6 & 88.0 & 12.2 & 1110.8 & 177.5 & 16.0 \\
Japan & 125.85 & 454.1 & 149.5 & 117.5 & 25.9 & 1051.6 & 347.2 & 33.0 \\
Germany & 80.31 & 323.9 & 164.8 & 66.4 & 20.5 & 648.7 & 229.0 & 35.3 \\
Korea & 51.64 & 301.0 & 246.3 & 88.2 & 29.3 & 594.3 & 261.3 & 44.0 \\
Australia & 23.71 & 144.3 & 243.9 & 44.3 & 30.7 & 261.4 & 156.6 & 59.9 \\
South Africa & 55.92 & 121.5 & 88.6 & 86.0 & 70.8 & 256.0 & 225.0 & 87.9 \\
Poland & 38.36 & 105.2 & 115.5 & 50.5 & 48.0 & 170.1 & 134.7 & 79.2 \\
World & 7587.46 & 13 864.9 & 76.0 & 3772.1 & 27.2 & 26 614.8 & 10 100.5 & 38.0 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a}In July 2019, according to the US Census Bureau, http://www.census.gov.
techniques cannot be used to extract coal safely and cleanly from complex deep geological environments, it has become necessary to explore new theories and technologies for deep coal exploitation that will address these existing global concerns.

We previously proposed an in situ fluidized mining technique to achieve in situ exploitation and conversion of deep underground coal resources. This technique involves transforming deep, solid coal into electric energy or gaseous/liquid state substances in situ, followed by transporting the fluidized resources to the ground surface, ultimately resulting in zero or near-zero carbon emissions and avoiding in situ geological formation damage. This is a promising strategy that addresses the previously mentioned problems that limit the achievement of coal safety, environmental protection, and economic mining and utilization. Figure 1 shows a schematic diagram of the fluidized mining plan. Realistically, the implementation of in situ fluidized mining of deep coal resources depends on whether or not the process is able to effectively protect the surrounding geological environment and avoid damage to the formation, as well as whether it can reduce the negative effects to the ground surface and ecological environments, such as increased greenhouse gas emissions, which are normally a result of traditional mining practices. At present, there is a lack of in-depth analysis and discussion on these issues.

In this study, we conduct a comparative analysis of different mining methods in terms of their potential to cause damage to geological formations and reduce greenhouse gas emissions. We compare, using a numerical simulation method, the (a) mining-induced stresses, concentrations, and failure within surrounding rocks, (b) surface subsidence, (c) microseismicity, and (d) the stratum environment for fluidized and traditional mining techniques. Moment tensors and energy are employed to determine the number and estimate the intensity of mining-induced microseismic events.

2 | MODELS AND METHODS

2.1 | UAMM models

To mine and utilize coal resources safely and cleanly, we designed a flexible unmanned automatic mining machine (UAMM) and a coal mine layout for deep in situ fluidized mining suitable for the machine, as shown in Figure 2. The UAMM design combines the functions of excavation, separation, supporting, fluidized conversion, and energy storage through a number of modules known respectively as the mining, supporting, coal separation, fluidized conversion, and energy storage modules. These modules have flexible connections, which allow for detachable assembly. By selecting the appropriate combination of modules, the UAMM can be used to excavate roadways and exploit coal seams. The operation and working status of the UAMM were controlled and monitored by a remote wireless control platform on the ground. Power-driven devices were set in each “function module,” which is a component that is able to move forward or backward autonomously according to remote monitoring instructions. The mining model simulation and application of the UAMM is herein described.

During mine construction, a combination of mining and supporting modules was used to excavate the shaft and roadway in the rock stratum. A rock-breaking mechanism, similar to the cutter head of a tunnel boring machine (TBM), was installed in front of the mining module and used to excavate the rock. After excavation, the supporting module provided high-intensity support for the shaft and roadway to ensure their stability. The simulated mine field (Figure 2A) was approximately quadrilateral, with two roadways running along the coal seam tendency and coal seam strike, featuring several crossheadings traversing the field along the coal seam tendency. There were two vertical shafts running diagonally into the mine field. These shafts extended from the ground surface down to the coal seam where they connected to the

![Schematic diagram of the fluidized mining method](image)
Coal seam roadway encircling the mine field. Multiple pipelines and cables were laid within the shaft, roadway, and crossheadings to facilitate energy transmission, signal transmission, and material supply between the coal seam and surface. In addition, multiple filling boreholes were drilled from the surface down to the crossheadings to connect with the filling pipe and facilitate the transportation of filling slurry required to fill the goaf.

As shown in Figure 2B, upon completion of the mine development, the simulated coal seam mining and fluidized conversion was achieved using the mining, coal separation, fluidized conversion, and energy storage modules of the UAMM. Mining was initiated at the corner of the deep coal seam mine field and excavated along strike. Forward coal mining was converted to backward coal mining according to a route-changing scheme when the mine boundary was reached. The coal was then mined in the other direction back toward the original boundary in a straight line. During the simulated coal seam mining stage, the coal was broken up by the mining module and then transferred to the separation module where the coal and gangue were automatically sorted. The gangue was then discharged from the chamber as filling material for the goaf while the separated coal was transported to the fluidized conversion module. This module converted the solid coal into gaseous, liquid, and gas-solid-liquid states, or into electrical energy in situ using fluidized conversion instruments. The fluidized resources were then transported to the ground surface through pipelines in the crossheadings and shaft. Once the coal seam between two adjacent crossheadings was fully mined, a retaining wall was constructed at the entrances of crossheadings and behind the UAMM to prevent the filling slurry from flowing into the crossheadings as well as to separate the UAMM from the strip-shaped goaf. Once these retaining walls were constructed, the filling slurry was transported to the goaf through the filling boreholes and filling pipelines to prevent surface subsidence. Finally, the gas and solid waste from the fluidized conversion process was discharged to the goaf, mixed with the filling slurry, and sealed inside.

2.2 Numerical simulation methods

Numerical simulations are widely used in coal mining as they are an effective technique to investigate underground geotechnical engineering. In this study, the continuum-based discrete element method (CDEM) was used to simulate coal seam excavation. This is a coupled approach that combines the accuracy of the finite element method (FEM) stress solutions, for continuum solids, with the flexibility of the discrete element method (DEM), for fracture propagation. This combination is a reliable and effective method for solving stress and fracture field problems and is also advantageous when simulating 3-D discontinuous deformation problems.
Two types of elements, that is, blocks and contacts, constitute the model constructed using the CDEM algorithm.\textsuperscript{46-49} The model was constructed based on the condition that the FEM was used for the inside of the block, whereas the DEM was applied for the interface. Every block within the model was required to satisfy Equations (1)-(5b), as follows.

The equilibrium equation:
\[
\nabla \cdot \boldsymbol{\sigma} = \rho \ddot{\boldsymbol{u}} + \boldsymbol{f} - \boldsymbol{u}, \quad x, y, z \in \Omega. \tag{1}
\]

The strain-displacement relationship:
\[
\varepsilon = \frac{1}{2} (\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T). \tag{2}
\]

The constitutive law:
\[
\boldsymbol{\sigma} = \mathbf{D} : \varepsilon. \tag{3}
\]

The boundary conditions:
\[
\begin{align*}
\boldsymbol{u} &= \bar{\boldsymbol{u}}, \quad \text{on } \Gamma_n, \tag{4a} \\
\boldsymbol{\sigma} \cdot \boldsymbol{n} &= \bar{\boldsymbol{f}}, \quad \text{on } \Gamma_c. \tag{4b}
\end{align*}
\]

The initial conditions:
\[
\begin{align*}
\boldsymbol{u} (t = 0) &= \bar{\boldsymbol{u}}^0, \quad \text{on } \Gamma_n^0, \tag{5a} \\
\boldsymbol{\sigma} (t = 0) \cdot \boldsymbol{n} &= \bar{J}^0, \quad \text{on } \Gamma_c^0. \tag{5b}
\end{align*}
\]

Here, \( \boldsymbol{u} (x, y, z) = (u (x, y, z), v (x, y, z), w (x, y, z) )^T \) is the vector displacement, \( \boldsymbol{\sigma} \) is the stress vector, \( \boldsymbol{f} \) is the body force vector, \( \rho \) is the density, \( c \) is the damping coefficient, \( \boldsymbol{u} \) is the displacement vector, \( \dot{\boldsymbol{u}} \) represents the velocity, \( \ddot{\boldsymbol{u}} \) represents the acceleration, \( \Gamma_n \) represents the displacement boundary, \( \Gamma_c \) the confining stress, \( \bar{\boldsymbol{f}} \), is prescribed on the external force boundary, \( \Gamma_n \), \( \bar{\boldsymbol{u}}^0 \), is prescribed on the initial boundary, \( \Gamma_n^0 \), and the confining stress, \( \bar{J} \), is prescribed on the initial external force boundary, \( \Gamma_c^0 \).

In the CDEM algorithm,\textsuperscript{46-49} the tensile and shear failure of the elements were determined by the maximum tensile-stress criterion and the Mohr-Coulomb strength criterion defined by Equations (6a) and (6b) as follows.

The tensile failure criterion:
\[
\sigma_n \geq \sigma_n. \tag{6a}
\]

The shear failure criterion:
\[
\tau \geq \sigma_n \tan \phi + C. \tag{6b}
\]

Here, \( \sigma_n \) is the normal stresses, \( \tau \) is the tangential stresses, \( \sigma_n \) is the tensile strength, \( C \) is the cohesion, and \( \phi \) is the internal friction angle. The initial geometric domain was separated into the finite element (FE) domain and the discrete element (DE) domain for the implementation of the fracture process in the algorithm. The contact between the FEs and DEs contains several normal and tangential springs.\textsuperscript{46-49} If either of these failure criteria is satisfied, the solid would rupture by separating at the node.

This method adopts an explicit iteration in the time domain of the calculation for the solution to the equation using the dynamic relaxation method. During the calculation process, the acceleration and velocity are iterated in different manners. The central difference scheme performs the former while the latter is by the unilateral difference scheme. The schemes can be expressed as follows\textsuperscript{46-49}:

\[
\begin{align*}
\bar{\dot{u}}^n_i &= \frac{\ddot{u}^{n-1}_i - \dot{u}^{n-1}_i}{(\Delta t)^2}, \tag{7a} \\
\bar{u}^{n+1}_i &= \frac{\ddot{u}^{n+1}_i - \dot{u}^{n+1}_i}{\Delta t}. \tag{7b}
\end{align*}
\]

where, \( \ddot{u}^n_i \), \( \dot{u}^{n+1}_i \), and \( \dot{u}^{n+1}_i \) represent the acceleration, velocity, and displacement, respectively, of the \( i \)th node of one element at the \( n \)th time step.

The explicit iteration technique can then be formulated from the following equations\textsuperscript{46-49}:

\[
\begin{align*}
\dot{u}^{n+1}_i &= \ddot{u}^n_i + \ddot{u}^{n+1}_i \Delta t, \tag{8a} \\
\dot{u}^{n+1}_i &= \dot{u}^n_i + \dot{u}^{n+1}_i \Delta t. \tag{8b}
\end{align*}
\]

In the iteration process, convergence is reached when the total magnitude of the kinetic energy is minimized. The solution to the displacement was available as a result of the previous discrete form of the governing equation and dynamic relaxation method. The stresses can be solved based on the strain-displacement relationship in Equation (2) and the constitutive relation law in Equation (3), such that the normal and tangential stresses on the nodes employed in Equations (6a) and (6b) can be transformed.

Microseismic events occur due to faint Earth tremors induced naturally or anthropogenically, accompanying displacements in the Earth’s crust. In mining engineering, underground mineral excavation causes the transfer and concentration of stress. The concentration of high stresses results in failure in the surrounding rock and microseismic emissions during the rock failure process.\textsuperscript{33,50,51} The relationship among
displacement, stress, and seismicity during mining-induced failure has been extensively examined in recent years, as well as being widely used in the monitoring of major mine disasters, such as roof collapse, mine water inrush, coal and gas outburst, and rock burst.\textsuperscript{51-53} Figure 3 illustrates a typical relationship between rock strata movement and microseismic activities.\textsuperscript{54} This shows that microseismic events occur when the roof rock strata rupture, where different numbers of microseismic events reflect different degrees of rupture. A mathematical representation of fault movement, known as a “moment tensor,” can calculate and store the initial information from displacements and present information on the magnitude and orientation of a seismic event. This information may be obtained for as long as the moment tensor is determined. Seismic events can be predicted via a numerical simulation method and used to predict potential risk with an increase in microseismic events. Based on Angus et al.,\textsuperscript{55} we can consider that a microseismic event occurred within the element when the effective stress satisfies the Mohr-Coulomb yield envelope. For the description of a seismic event based on moment tensors, the true stress was employed to express a moment tensor through a stress “drop,” which is the temporal difference in stress that occurred before and after an event.\textsuperscript{42} The moment tensor can be calculated using this method, and the microseismic event number can be obtained by analyzing the moment tensor through the stress drop.

The differential stress, $\Delta \sigma e$, both before and after an event, is calculated over a single time step, such that the eigendecomposition of the drop in the effective stress tensor can be performed as follows:\textsuperscript{42}:

$$\Delta \sigma e \mathbf{v} = \lambda \mathbf{v},$$

where $\mathbf{v}$ is the eigenvector and $\lambda$ is the eigenvalue. Eigenvalues are used to scale the eigenvector, thus resulting in the definition of the moment tensor, $\mathbf{M}$, defined as follows:\textsuperscript{42}:

$$\mathbf{M} = \lambda \mathbf{v}.$$  

The unit eigenvector is used to rotate the moment tensor to its principle direction, such that the moment tensor can then be calculated.

### 2.3 Geological formation model and parameters

The longwall mining method is widely used to exploit coal resources because of its high efficiency.\textsuperscript{56} In this study, the longwall mining method was adopted as a traditional mining method for comparison with the fluidized mining method. Therefore, two different mining methods were simulated to mine the same coal seam. Figure 4 shows the coal mine layout when the same coal seam is mined using different coal mining methods. To compare characteristics such as stope stress distribution, roof subsidence, coal wall failure, and microseismicity for the fluidized and traditional mining practices, the direct distance of each crossheading in the fluidized mining layout was defined so that it was equal to the length of the working face in the longwall mining method. In the fluidized mining method, the range of each filling in the goaf is the area between the two crossheadings. Hence, we selected the same area from the mine field for this simulation to compare the geological damage that resulted from the different mining methods. The simulation was based on the geological conditions of working face 31010 at coal mine No. 12 in the Pingmei group, which is located in the central part of Henan Province, China.\textsuperscript{57,58} Figure 5 shows the location and stratigraphic column of working face 31010. The average burial depth is approximately 1100 m.

In accordance with the geological characteristics of the strata, a numerical model was established, as shown in Figure 6. In the model, one panel and two gateways (crossheading) were excavated. Considering the actual situation at the site, the width of the panels was set to 300 m ($Y$ direction in the model), roadway was set to $4 \times 3$ m ($Y \times Z$), and mining distance was set to 200 m ($X$ direction in the model). Moreover, a 50-m-wide border pillar was placed on each
side of the model to eliminate the influence that the boundary conditions have on the calculation results. The thicknesses of the coal seam, roof strata, and floor strata were 3, 93, and 34 m, respectively, and the model size was set to $300 \times 408 \times 130$ m ($X \times Y \times Z$) in the numerical simulation. To generate a suitable mesh, the thickness of the strata was set as an integer (inevitably an approximation) according to the prevailing conditions. The established model consists of approximately three million elements. The minimum mesh size of the coal seam section was 1 m, which gradually increased with increasing distance from the coal seam. According to the stratigraphic column of working face 31010, the actual buried depth of the coal seam in the modeling area is 1000 m while the thickness of the unmodeled rock strata above the model is 900 m. The vertical in situ stress, $\sigma_v$, is given by the overburden pressure as follows:

$$\sigma_v = \gamma H,$$

where $\gamma$ is the unit weight of the rock mass and $H$ is the depth below the ground surface. The unit weight of the overlying rock mass was assumed to be 25 kN/m$^3$. Therefore, a uniformly distributed pressure of 22.5 MPa was applied to the upper boundary of the model to simulate the self-weight stress imposed by the unmodeled overlying strata. The side boundaries were constrained by horizontal displacement, whereas the bottom boundary was constrained by horizontal and vertical displacements. In this simulation, the coal seam and roof strata were set as the DE domain. If either of the normal and tangent springs that connect the elements in the DE domain satisfied the fracture criteria in Equations (6a) and (6b), the solid would rupture by separating at the node. During the extraction process, the interface of the element would separate if the normal or tangential stress satisfied the fracture criteria. Due to the unloading effect, the newly separated interface of elements would continue to deform, finally evolving into a typical tensile or shear fracture, which would result in coal wall failure and roof collapse.
as the working face advances. The fracture criteria for tensile and shear failure involve the parameters of the rock material, such as the tensile strength, cohesion, and internal friction angle. In accordance with experimentally determined parameters, Table 2 lists the distributions of the coal-rock layers and mechanical parameters used in the model. The contact surface

**FIGURE 6** Numerical model dimensions for the (A) front view and (B) top view of the coal seam

**TABLE 2** Coal-rock layers and mechanical parameters used for the numerical model

| Lithology          | Thickness (m) | Density (kg/m³) | Cohesion (MPa) | Friction angle (deg.) | Tensile strength (MPa) | Poisson's ratio | Elasticity modulus (GPa) |
|--------------------|---------------|-----------------|----------------|-----------------------|------------------------|-----------------|--------------------------|
| Fine sandstone     | 28            | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| Siltstone          | 10            | 2510            | 5.0            | 36                    | 3.5                    | 0.28            | 14.07                    |
| Mudstone           | 16            | 2460            | 4.0            | 30                    | 2.5                    | 0.33            | 10.09                    |
| Kern stone         | 14            | 2630            | 6.5            | 33                    | 6.0                    | 0.26            | 21.94                    |
| Fine sandstone     | 6             | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| White sandstone    | 5             | 2510            | 5.0            | 36                    | 3.5                    | 0.28            | 14.07                    |
| Sandy mudstone     | 6             | 2510            | 5.0            | 36                    | 3.5                    | 0.28            | 14.07                    |
| Fine sandstone     | 3             | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| Sandy mudstone     | 5             | 2510            | 5.0            | 36                    | 3.5                    | 0.28            | 14.07                    |
| No. 15 coal        | 3             | 1450            | 2.5            | 28                    | 1.5                    | 0.30            | 7.012                     |
| Fine sandstone     | 5             | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| Limestone          | 4             | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| Fine sandstone     | 10            | 2550            | 7.5            | 32                    | 5.5                    | 0.28            | 18.18                    |
| Mudstone           | 15            | 2460            | 4.0            | 30                    | 2.5                    | 0.33            | 10.09                    |
| Filling material   | 3             | 1450            | 2.5            | 28                    | 1.5                    | 0.30            | 7.012                     |
elements between the strata were shared nodes, and different node parameters were assigned according to the materials of the elements where the contact surfaces were located. The two nodes were connected by springs. When the minimum fracture criteria were satisfied, the nodes were separated and cracks were generated.

The excavation scheme was the same for both mining methods with respect to the following processes: (a) establishing the model, setting the boundary conditions, and balancing the initial stresses; (b) excavating gateways 1 and 2; and (c) excavating the coal seam 200 m along the X direction in 5 m intervals and simulating coal seam mining. However, there were differences in the treatment of the goaf. This is because traditional mining adopts the caving method to treat the goaf, which allows the roof strata behind the advancing face to collapse to fill the goaf. In contrast, the fluidized mining method uses the filling method to treat the goaf, where the goaf is immediately filled after each excavation, followed by the next excavation. We assumed that the goaf in the fluidized mining method was completely filled. Therefore, to obtain the stop stress distribution and roof subsidence characteristics, a monitoring line was arranged in the middle of the roof rock layer 25 m above the coal seam, which monitored the stress and roof subsidence during the mining process.

3 | RESULTS AND ANALYSIS

3.1 | Distribution of surrounding rock stresses

In general, the distribution of vertical stresses has a significant effect on coalface failure. To compare the vertical stress distribution in the surrounding rocks at various mining distances, the vertical stress in front of the working face was obtained along a monitoring line in the middle of the coal seam. The coordinates of each node are not regular numbers as the coal seam is composed of randomly distributed tetrahedral elements with a side length of 1 m, such that the coordinates of the nodes obtained using the monitoring line of different mining methods are not entirely consistent. Figure 7 plots the distribution of the vertical stresses in front of the working face with the traditional longwall mining and fluidized mining techniques, which was recorded at excavation distances of 50, 100, and 150 m. The distribution of the advanced abutment stress was similar for both mining techniques. However, for traditional mining, the values indicated that, as the mining distance increased, the peak value of the advanced abutment stresses in front of the coal wall gradually increased. The peak values of the abutment stress were 63, 78.3, and 85.5 MPa, respectively. For fluidized mining, the excavation distance had little effect on the peak values, which were 53.7, 46.5, and 52.6 MPa, respectively. Figure 8 demonstrates that the peak and range of the advanced abutment stress were smaller for fluidized mining than those of traditional mining at the same excavation distance. When mining at 50, 100, and 150 m, fluidized mining reduced the stress peak values by 9.4, 31.8, and 32.9 MPa, respectively. In addition, the stress concentration factors were reduced from 2.5, 3.2, and 3.4 to 2.2, 1.9, and 2.1, respectively.

The distribution of the abutment stress can be generally characterized by three stress zones, that is, stress relaxation, stress concentration, and in situ stress zones. A horizontal dashed line and a vertical dashed line were drawn, as shown in Figures 7 and 8, to demarcate the stress-relaxation zone, stress concentration zone, and in situ stress zone. The horizontal demarcation line has a value 1.05 times the measured in situ stress according to previous studies. The stress

**FIGURE 7** Vertical stress distribution at different excavation distances for the (A) fluidized and (B) traditional mining methods.
relaxation zone occurs in the vicinity of the coal wall as excavation causes the release of stress. As the distance from the coal wall increases, the stress in the coal increases sharply and then gradually decreases once there is a peak in the advanced stress; however, the stress remains greater than the in situ stress. As the distance from the coal wall increases further, the stress gradually decreases to match that of the in situ stress. The results indicate that the range of the stress concentration zone for the traditional mining method is significantly larger than that for the fluidized mining method. The range and intensity of the abutment stress would be significantly reduced with the use of fluidized mining. The stress concentration caused by excavation sharply increases the energy accumulated in the surrounding rock. When disturbed by mining, this accumulated energy in the surrounding rock is released instantaneously, which could result in a severe power disaster accident, equipment damage, or casualties. In this simulation, the fluidized mining method significantly reduced the stress concentration factor, thereby reducing the accumulation of energy in the surrounding rock and reducing the risk of power disasters.

3.2 Coal wall failure

During the calculation process, to obtain and compare the pattern of fractures and the characteristics of deformation on the coal wall at different distances, the results of the displacements and fracture patterns on the coal wall at the time of extraction at distances of 50, 100, and 150 m were output. Figure 9 demonstrates the characteristics of coal wall failures associated with fluidized and traditional mining techniques at an extraction distance of 50, 100, and 150 m. The coal wall failures occurred in both cases when extracting coal resources from deep underground. Rib spalling, a type of wall failure, occurs when the internal fractures propagate and connect with the coal wall. Figures 10 and 11 show the displacement in the coal wall at an extraction distance of 50, 100, and 150 m. The maximum displacement in the X direction is mainly concentrated in the middle of the coal wall, the maximum displacement in the Z direction is mainly concentrated in the top and bottom of the coal wall, and the coal wall has a larger displacement in the traditional mining method. A comparison of Figures 9-11 shows that the area with large displacement on the coal wall was the area where coal wall failure occurs, cracks appear in the margin of the large displacement area, and there were more interconnected fractures in the coal wall, as well as the presence of more serious rib spalling with the use of traditional mining. The results indicate that there was less failure in the coal wall throughout the mining process with the use of fluidized mining; there was no damage during certain periods. As shown in Figure 12, no failures occurred with the fluidized mining method, but there was considerable rib spalling at certain points with the traditional mining approach.

Sketches of coal wall rib spalling were obtained based on long-term field observations, as shown in Figure 13. This included types of coal wall failure identified as upper spalling,
middle spalling, bottom spalling, upper and bottom spalling, and whole spalling. Comparisons show that the coal wall failures obtained via the simulation were consistent with the field observations,\textsuperscript{62} which demonstrates the reliability of the simulation results. Therefore, we infer that this simulation can accurately predict coal wall failures during mining. We note that coal wall spall is another common failure phenomenon in traditional working coalfaces. This phenomenon disturbs the mining process and may cause equipment damage or lead to casualties, rendering it a major difficulty that affects the safety of mining.\textsuperscript{43,63} Coal wall failures mainly depend on the stress in the surrounding rock. When this stress exceeds the maximum strength of the coal body, failure will occur in the coal wall. According to our simulation results, fluidized mining significantly reduced the stress in the surrounding rock, thereby reflecting a reduced failure rate and improved stability in the working coalface.

### 3.3 Roof subsidence

Figure 14 shows the monitoring results for roof subsidence after the excavation of 200 m of the coal seam. The results show that the subsidence value of the roof strata was significantly lower with fluidized mining than traditional mining. The maximum subsidence values were 48.3 and 4.3 cm, respectively. For the roof subsidence process, fluidized mining uses the backfilling method to control strata movement and deformation, such that we can effectively control subsidence of the overburden. In contrast, traditional mining uses the caving method to treat the goaf, which causes movement of the overlying strata, deformation leading to surface subsidence, and damage to the geological formation after mining of the coal seam. In our simulation, fluidized mining effectively controlled the movement of the overlying strata and avoided surface subsidence caused by
3.4 | Microseismic event analysis

The rock layer contained 48,732 nodes and the stress at each node was obtained from the numerical simulation. According to the simulation results, the stress results of each node when reaching calculation balance during the excavation process...

traditional mining. Therefore, the use of fluidized mining to extract coal resources can reduce the risk of damage to the surrounding geological formation and avoid hazards, such as surface modifications and escarpment landslides, as well as damage to farmland, houses, roads, and groundwater systems.
can be obtained, and $M$ of each node can be calculated according to Equations (9) and (10). As disturbance from the excavation of the gateway is weaker on sandstone strata 25 m above the coal seam, microseismic events were assumed to be absent in the sandstone strata during the excavation of the roadway. Therefore, the maximum $M$ during gateway excavation was selected as the threshold to determine whether a microseismic event has occurred during coal mining. If the $M$ calculated during the mining process is greater than this threshold, there was an occurrence of microseismic events.

Therefore, the number and distribution of microseismic events in the sandstone strata 25 m above the coal seam were obtained.\textsuperscript{42,64} The distribution and number of microseismic events were obtained for mining at distances of 50, 100, 150, and 200 m, as shown in Figures 15-17. The numbers of nodes that experienced microseismic events with fluidized mining were 7632, 13 424, 20 104, and 25 856, which accounted for 16%, 28%, 41%, and 53% of the total nodes, respectively. With traditional mining, the numbers of nodes were 17 704, 26 972, 33 732, and 40 444, which accounted for 36%, 55%, 69%, and 83% of the total nodes, respectively. This shows that the number of microseismic events increased with the coal seam mining distance. Traditional mining resulted in a comparatively wide distribution of microseismic events with high density in the rock layer. This is because, from our perspective, the roof strata collapsed, causing a greater disturbance range in the adjacent rock strata. As the mesh size gradually increases with the distance from the coal seam, the mesh size of the sandstone strata becomes larger. This results in the nodes of the elements in the sandstone strata mainly distributed at the upper and bottom parts of the strata while the number of nodes in the middle of the sandstone strata is smaller. Therefore, the distribution of microseismic events is mainly concentrated on the upper and bottom parts of the strata, but few nodes in the middle. Due to the dependence of the calculation results on the quality of the mesh, there may be a certain difference between the distribution regularity obtained from the simulation and that obtained from field monitoring.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig14.png}
\caption{Roof subsidence for the fluidized mining (circular data points) and longwall mining (triangular) techniques.}
\end{figure}

\begin{figure}[h]
\centering
\begin{subfigure}{0.49\textwidth}
\includegraphics[width=\textwidth]{fig15a.png}
\caption{(A)}
\end{subfigure}
\begin{subfigure}{0.49\textwidth}
\includegraphics[width=\textwidth]{fig15b.png}
\caption{(B)}
\end{subfigure}
\begin{subfigure}{0.49\textwidth}
\includegraphics[width=\textwidth]{fig15c.png}
\caption{(C)}
\end{subfigure}
\begin{subfigure}{0.49\textwidth}
\includegraphics[width=\textwidth]{fig15d.png}
\caption{(D)}
\end{subfigure}
\caption{Distribution of the microseismic events during fluidized mining at excavation distances of (A) 50, (B) 100, (C) 150, and (D) 200 m.}
\end{figure}
Microseismic emissions during the rock failure process are induced by coal extraction, which is also accompanied by energy release. The energy released can be used to evaluate the microseismic event. The energy of each node can be calculated as follows:

\[ E = \frac{1}{2} \left( \delta_x e_x + \delta_y e_y + \tau_{xy} y + \tau_{yx} x + \tau_{x} y + \tau_{y} x \right) V. \]  

(12)

Therefore, the energy difference before and after a microseismic event is calculated to quantify the intensity of the microseismic event. Figure 18 shows the energy distribution regularity of the microseismic events. There are more small energy events in the fluidized mining method while there are more large energy events in the traditional mining method. The traditional mining method has stronger disturbance and causes more serious damage to the adjacent rock strata. The numerical results imply that earthquakes caused by fluidized mining have lower magnitudes than those caused by traditional mining due to lower energy releases from microseismic emissions.
events in the fluidized mining method. Moreover, the basic principle of induced seismicity states that the pressure build-up caused by coal seam mining reduces the effective stresses in the adjacent rock strata that move the stress state closer to failure. If failure conditions are reached, the elastic energy stored in the rock mass is released sharply, inducing a microseismic event.65 Our results indicate that, when fluidized mining is used to extract coal from deep underground, there is a reduction in the range of the disturbance and pressure build-up in the surrounding rock. This would decrease the risk of adjacent rock strata reaching failure conditions and thus reduce the risk of earthquakes induced by coal seam mining.

4 | CONCLUSIONS

In situ fluidized mining is a promising approach for the exploitation and utilization of the vast amount of deep underground coal resources. To reflect the advantages of fluidized mining, a numerical method was used to compare the mining-induced stresses, concentration, failure in surrounding rocks, surface subsidence, and microseismicity with the fluidized and traditional mining techniques. The results demonstrated that the fluidized mining of deep coal can reduce the (a) range and intensity of surrounding rock stress concentration, (b) accumulation of energy in the surrounding rock, (c) risk of power disasters, (d) rate of failures and improve the stability of the working face, and (e) risk and intensity of mining-induced earthquakes. This technique can also effectively limit movement in the overlying strata and prevent damage to the geological formation, which is associated with numerous hazards caused by surface subsidence.

In contrast to traditional mining approaches, we show that the proposed method achieves the safe and clean mining of deep underground coal resources. However, this preliminary study has several limitations. First, considering the primary purpose of this study, the effects of the mining height, filling material properties, goaf filling rate, and direct distance of the crossheadings were not considered in the numerical simulation. Future studies will therefore focus on the effect that these variables have on the stability of the surrounding rock and geological formation damage during fluidized mining. In addition, the CDEM, combining the advantages of the FEM and DEM, was used to analyze the damage to the surrounding rock from different mining methods. However, the CDEM has the limitation that the fracture pattern depends on the mesh quality. The problem of the dependence of the calculation results on the mesh quality will be solved in future studies.

Second, we have not thoroughly examined several factors that could significantly influence the potential application of this promising method in actual engineering problems. For instance, the comprehensive cost associated with UAMM-based mining is a non-negligible factor when applying the proposed technology in practice. In general, the “conventional coal cost per ton” is the total cost of a coal product divided by the output of raw coal. However, this calculation is not all-inclusive because it does not include the costs related to other aspects that directly the impact calculation accuracy (e.g., coal waste in traditional mining and environmental pollution caused by post-mining transportation and utilization). Thus, the “comprehensive cost of coal per ton” is a better representation of the true cost and is defined as the coal cost per ton, including waste and environmental costs. However, UAMM-based mining is currently not used for rock and coal seam exploitation. TBM, which has several structural and functional similarities with the UAMM, has been used in several coal mines in China to construct inclined shafts, adits, and roadways. Referring to the estimation method for TBM costs, as a rough estimation, we calculated the potential cost for each of the simulated mining techniques based on the simulated mining layouts, finding that the UAMM-based mining cost per ton is 2.38 times the conventional coal cost per ton.38 This result indicates that the total cost of UAMM-based fluidized mining is approximately 49% of traditional mining costs. The “comprehensive coal cost per ton” is at least 4.8 times greater than the conventional coal cost per ton.38 Considering further operational costs, the fluidized mining system employs a simple roadway layout, which would reduce the required amount of roadway excavation and improve the recovery rate of coal resources. This is because, unlike the traditional exploitation and utilization of coal resources, the coal would be converted into fluidized resources and transported to the ground, which would significantly reduce the cost of energy transportation. Furthermore, the cost of capturing, transporting, and storing CO₂ would also be reduced because the gas generated during fluidized conversion and utilization would be directly solidified in situ into the goaf. Considering the objectives of this study, we intend to discuss this issue in detail in our follow-up investigations.

The potential decarbonization of fluidized mining is also a concern. In general, previous studies regarding the challenge of reducing carbon emissions have focused on carbon capture and storage technologies.66-70 The mined-out areas that remain after deep coal resources are mined via fluidized mining are conducive to the geological storage of CO₂ because the goaf and ground surface are separated by more than 1000 m of low permeability rock. The CO₂ generated by the in situ fluidized conversion process is mixed with filling slurry and solidified in the goaf to achieve a low-carbon, clean utilization of coal resources. Assuming that half of the global coal resources were mined and utilized (i.e., 9 trillion tons), this would generate 27 trillion tons of CO₂, which is nearly 900 times the total carbon emissions in 2018.71 If fluidized mining is used, this CO₂
would be completely sealed within the goaf with the filling slurry during the mining process. Thus, our method offers significant advantages in terms of its decarbonization potential. We will discuss decarbonization in detail in our future studies.

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CONFLICT OF INTEREST
The authors declare that they have no known competing interests.

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