Characteristics of fracture field in different stress zones during multi-seam mining: Quantification based on theoretical analysis and BBM-DEM accurate simulation method

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Abstract
The revelation of the distribution characteristics of stress and fractures in the floor strata is of great significance to improve the regional gas drainage efficiency and to eliminate or reduce the risk of coal and gas outburst in adjacent coal seams during multi-seam mining. In this paper, the stress distribution in the floor under mining condition was derived, and the characteristics of stress zones in the floor were elaborated while mining the 22201 working face in Shaqu coal mine in Shanxi province, China. Besides, the propagation laws of fractures in different stress zones were theoretically analyzed, and the distribution law of fracture angles in the floor strata under different mining-induced stresses was obtained. The research results demonstrate that the compression and transition zones show high vertical stress and less developed fractures and are dominated by fractures with a large angle (>60°), which is unfavorable for gas drainage. The expansion zone in the floor within 2-40 m in the rear of the working face is characterized by high unloading degree of vertical stress and developed fractures. Moreover, fractures with a small angle (<60°) dominate the spatial distribution of the fractures, which is favorable for gas drainage. The research results can not only be a beneficial supplement to the theory of coal and gas co-exploitation in multi-seam mining but also provide theoretical support for optimizing the design parameters of cross-measure boreholes under similar conditions.

Keywords
BBM-DEM, gas drainage, Griffith criterion, mining-induced stress, zoning of fractures
1 | INTRODUCTION

As mining depths increase, new challenges such as coal and gas outburst induced by mining activities have emerged, particularly in gassy multi-seam mining. Protective layer mining is proved an economical and effective method to reduce stress, increase coal permeability and improve regional gas drainage efficiency, and to eliminate or reduce the risk of coal and gas outburst in adjacent coal seams under multi-seam mining. Presently, a large number of mature application bases have been obtained. The mining of the upper protective layer is less destructive to the lower protected coal seam, and the construction is simple and common. After mining the upper coal seam layer, because of strata subsidence and caving mining, stress concentration of the surrounding rock will occur and transfer to the coal and rock at the floor, which further cause stress change and rupture of surrounding rock at the floor and the lower coal mass. The mining-induced stress change and rupture of the surrounding rock will not only have a critical effect on the roadway excavation and coal mining but also be of great importance for the gas drainage boreholes arrangement. Therefore, the revelation of mining-induced stress distribution and fracture characteristics in the floor of a coal seam is of critical significance for the high-efficiency gas drainage.

Coal mining will cause changes in surrounding rock stress field and fracture field. There are many kinds of hypothesis and theory, such as the pressure arch hypothesis, articulated rock beam, masonry beam theory, the key strata theory, and the theory of O-type circle. The ideas with engineering guidance significance such as “three horizontal zones,” “three vertical zones,” and O-type unloading circle were put forward on the basis of the above proposed theories. In recent years, with the improvement of the conditions of engineering practice, the research on the mining-induced stress field and fracture filed was conducted by many scholars on the basis of more abundant experimental data. Borehole peep method, line measuring method, and window measuring method were used by Peng to observe the mining-induced fractures, and the effect of the mining-induced fracture field on the stress distribution and gas migration was investigated using COMSOL Multiphysics software. Xiong used three borehole-based methods to investigate the movement laws of overburden strata and found that the overlying strata could be divided into four sections. A 3D numerical extraction model was built based on the geologic and mining conditions of Jining coal mine to reveal the changes and characteristics of the reconstructed vertical and lateral stress in rock interlayer after the mining of the protective seam. The three-dimension numerical simulation through the combination of COSFLOW software and Fluent software was performed by Guo et al. was applied to elaborate the mining-induced pressure-relieving of surrounding rock, variation in permeability and gas flow rules, and to determine the range of the high torus. Chen et al. analyzed the distribution rule of fractures in underlying coal rock mass in shallow buried deep protective layer mining, that is, the majority of the fractures are separation fractures, which is accompanied by a small number of penetration fractures. Ji measured the permeability of mining-induced pressure-relieving coal and believed that the permeability of the protected layer was related to the stress state of coal. Above all, most of the current related research mainly explores the mining-induced stress on the floor and the distribution laws of the failure range, but the in-depth quantitative analysis of the fracture distribution in different stress zones during multi-seam mining is still insufficient.

In this paper, based on the existing related research foundation, the in-depth investigation using elastic mechanics and accurate simulation analysis was conducted to elaborate the mining-induced floor stress distribution and fracture evolution in different partition under multi-seam mining. The research achievements can provide the theoretical and technical support for the practice of co-exploitation of coal and gas under the condition of the coal seam group with close distance.

2 | DISTRIBUTION LAWS OF MINING-INDUCED STRESS IN THE FLOOR OF A COAL SEAM

2.1 | Establishment of mechanical model

After mining coal seams, the in situ stress field around the stope is redisturbed, and this forms advanced abutment pressure in front of the working face, which moves forwards with the advancement of the working face. The changes in the stress of the surrounding rock can induce corresponding changes and redistribution of the floor stress in the stope. Based on the distribution characteristics of abutment pressure and anelastic mechanics analysis, a
simplified mechanical model for calculating the mining-induced stress in the floor in the front and rear of the working face was built, as shown in Figure 1. In the figure, \( \gamma H, k, \) and \( d \) represent the vertical stress in vertical direction, the stress concentration factor, and the length that the residual abutment pressure falls back to in situ stress in the goaf, respectively; \( f \) and \( e \) indicate the undisturbed in situ stress zone in front of the working face and the recovery zone of in situ rock stress in goaf. Moreover, \( a \) and \( b \) denote the length that the advanced abutment pressure falls back to in situ stress zone from the peak, and \( \gamma \) and \( H \) represent the average unit weight (kN m\(^{-3}\)) of overlying strata and the buried depth of the coal seam, respectively.

Based on the theory of elastic mechanics, the expressions of abutment pressures \( \sigma_\gamma \) and \( \sigma_z \) acting on the floor of the coal seam at point \( M (y, z) \) are shown as follows.\(^{30,41} \)

\[
\begin{align*}
\sigma_\gamma &= \frac{k\gamma H x}{\pi a} \left( \arctan \frac{a-x}{y} + \arctan \frac{x}{y} \right) + \frac{k\gamma H x}{\pi a} \frac{a-x}{y^2 + (a-x)^2} - \frac{H \gamma}{\pi} \frac{d + c + x}{y} \\
&- \frac{H \gamma}{\pi} \frac{a-b-x}{y} - \frac{H \gamma}{\pi} \frac{a+b-x}{y^2 + (a-b-x)^2} + H \gamma + \frac{(1-k) H \gamma y^3}{\pi b} \\
&+ \left[ (1-k) (x-a) + bk \right] H \gamma y \left( \arctan \frac{a+b-x}{y} - \arctan \frac{a-x}{y} \right) \\
&\times \left[ \frac{1}{y^2 + (a-x)^2} - \frac{1}{y^2 + (a+b-x)^2} \right] - \frac{H \gamma y^3}{\pi d} \left[ \frac{1}{y^2 + (d+c+x)^2} - \frac{1}{y^2 + (c+x)^2} \right] \\
&- \frac{(x+c) H \gamma y}{\pi d} \left[ \frac{d+c+x}{y^2 + (d+c+x)^2} - \frac{c+x}{y^2 + (c+x)^2} \right] \\
&- \frac{(x+c) H \gamma}{\pi b} \left( \arctan \frac{d+c+x}{y} - \arctan \frac{c+x}{y} \right) \\
\end{align*}
\]

\[
\begin{align*}
\sigma_z &= \frac{k\gamma H x}{\pi a} \ln \frac{y^2 + (a-x)^2}{y^2 + x^2} + \frac{k\gamma H x}{\pi a} \left( \arctan \frac{a-x}{y} + \arctan \frac{x}{y} \right) + \frac{k\gamma H x (x-a)}{\pi \left[ y^2 + (a-x)^2 \right]} + \\
&+ \frac{H \gamma y (a+b-x)}{\pi d \pi b} \left[ \frac{1}{y^2 + (a+b-x)^2} - \arctan \frac{a-b-x}{y} \right] \\
&\times \frac{H \gamma y (a+b-x)}{\pi d} \left[ \frac{c+x}{y^2 + (c+x)^2} - \frac{d+c+x}{y^2 + (d+c+x)^2} \right] \\
&- \frac{H \gamma y (x+c)}{\pi d} \left[ \frac{d+c+x}{y^2 + (d+c+x)^2} - \frac{c+x}{y^2 + (c+x)^2} \right] \\
&- \frac{H \gamma}{\pi d} \left[ \arctan \frac{d+c+x}{y} + \frac{H \gamma y (d+c+x)}{y^2 + (d+c+x)^2} \right] \\
&- \frac{H \gamma (1-k)(x-a) + bk}{\pi b} \left[ \frac{a+b-x}{(a+b-x)^2 + y^2} - \arctan \frac{a-x}{(a-x)^2 + y^2} \right] - \frac{H \gamma}{\pi} \arctan \frac{a+b+x}{y}
\end{align*}
\]

### 2.2 Evolution of mining-induced stress in the floor of the coal seam

To make the theoretical analysis more visible, geological conditions of 22201 longwall panel were used to show the evolution of mining-induced stress in different level of floor. Specific parameters are as follows: \( H = 500 \text{ m}, \) \( \gamma = 2500 \text{ kN/m}^3, \) \( k = 2.6, \) \( a = 10 \text{ m}, \) \( b = 40 \text{ m}, \) \( c = 10 \text{ m}, \) and \( d = 50 \text{ m}. \) By substituting the above parameters into Equations (1) and (2) \( \sigma_\gamma = f_1 (y, z) \) and \( \sigma_z = f_2 (y, z), \) \( M (x, y) \) can be obtained. To make the results more vivid, \( \sigma_{\gamma_5} = f_1 (y, 5), \) \( \sigma_{\gamma_{10}} = f_1 (y, 10) \) and \( \sigma_{\gamma_{15}} = f_1 (y, 15) \) as well as \( \sigma_{z_5} = f_2 (y, 5), \) \( \sigma_{z_{10}} = f_2 (y, 10) \) and \( \sigma_{z_{15}} = f_2 (y, 15) \) at the depth of \( z = 5 \text{ m}, \) \( 10 \text{ m} \) and \( 15 \text{ m} \) from the floor of the working face were selected to show the evolution of mining-induced stress see Figures 2 and 3.
because of the recovery of vertical stress in this zone, which belongs to a recompaction zone, as demonstrated in Figure 2.

As for the horizontal stress, the horizontal stress in the floor at the same depth shows an increase and decrease trend similar to that of vertical stress along the advance direction of the working face, and fluctuation amplitude and gradient of the curves of horizontal stress at different depths are more moderate than the curves of vertical stress in the same position. Taking $\sigma_{yz} = f_1(x,y)$ at 5 m in the floor of the working face as an example, we can conclude that horizontal stress $\sigma_y$ maintains at 0.77$\gamma H$ at the position 40 m in front of the working face and changes slightly in the compression zone. Furthermore, the horizontal stress reduces to about 0.45$\gamma H$ due to the pressure relief in the expansion zone 12 m behind the working face, and the maximum amplitude of pressure relief is only 41.5%. In the recompaction zone, the horizontal stress returns to 0.65$\gamma H$ and remains stable in this zone with a stress recovery ratio of 0.84.

In conclusion, in the same depth range, the amplitude and the gradient of the curves of the vertical stress are more sensitive than that of the horizontal stress. The changes in the curves of the vertical stress and horizontal stress tend to be gentle with increase in floor depth, and the stress concentration factor $k$ approximates to 1, indicating that the mining disturbance weakens with increase in floor depth. As shown in Figure 3, the smaller the floor depth, the larger the difference between $\sigma_y$ and $\sigma_z$, and the more obvious the influence of mining. In the advance process of the working face in the upper coal seams, coal and rock mass in the floor in the front and rear successively undergo a change from stress increase (compression zone) to stress decrease (expansion zone) and then to stress recovery (recompaction zone). The above zones advance synchronously with the working face.

3 | CHARACTERISTICS OF THE FRACTURE FIELD IN DIFFERENT STRESS ZONES DURING MULTI-SEAM MINING

The research on fractures in coal and rock strata of the floor induced by mining of the upper coal seams can not only guide the practice of gas drainage in a coal seam group but is also of great significance for managing mining-induced pressure and the controlling surrounding rocks under the mining condition of a coal seam group. Microscopically, the instability and fracturing of coal and rock strata essentially depend on their physical and mechanical properties, boundary condition, and stress state; macroscopically, the corresponding change in mining-induced stress in the floor determines and affects the failure range and distribution characteristics of fractures in the coal and rock mass.
3.1 Mechanical analysis of fracture evolution in floor strata in different mining-induced stress zones

Based on the analysis in the last section and the characteristics of different stress states of coal and rock mass in the floor, the coal and rock mass in the floor during the mining of 22201 working face in Shaqu coal mine was divided into four zones, namely a compression zone, a transition zone, an expansion zone, and a recompaction zone, as displayed in Figure 4.

Natural coal and rock mass form a complex geological body with geological discontinuity and plenty of meso- and micro-defects inside. According to the Griffith criterion, there are small cracks in all directions inside the rock mass. When a rock mass containing such small cracks is subjected to external loads, stress concentrates at the ends of these small cracks. The concentrated stress at the ends of some cracks (hereinafter referred to as fractures with propagation trend) preferentially reaches to the limit of tensile strength and then force the cracks to expand and develop, finally leading to the fracturing of the rock blocks. Based on elastic mechanics and some necessary assumptions, the equation of Griffith’s strength curve can be deduced, as shown in Equation (3).\(^{45}\)

\[
\tau_{yx}^2 = 4R_f^2 - 4R_f \cdot \sigma_y
\]  

By analyzing Equation (3), the following equations can be obtained.

When \(\sigma_1 + 3\sigma_3 < 0\),

\[
\sigma_3 = R_f
\]  

\[
\beta = 0
\]  

When \(\sigma_1 + 3\sigma_3 > 0\),

\[
\beta = \frac{1}{2} \arccos \frac{\sigma_1 - \sigma_3}{2(\sigma_1 + \sigma_3)}
\]

where \(\sigma_1\) and \(\sigma_3\) indicate the maximum and minimum principal stress, respectively; \(\tau_{yx}\) and \(\sigma_y\) represent the shear stress and normal stress on the elliptical fracture plane with propagation trend, respectively, and \(R_f\) and \(\beta\) denote the uniaxial compressive strength of the rock and the angle between the long axis of the elliptical fracture with the propagation trend and the maximum principal stress \(\sigma_y\), respectively.

Obviously, Equation (3) is a parabolic equation and each point on the parabola is a tangent with a limit Mohr’s circle determined by the corresponding \(\sigma_1\) and \(\sigma_3\), as demonstrated in Figure 5. This means that when the rock block is subjected to the effects of \(\sigma_1\) and \(\sigma_3\) of a certain limit Mohr’s circle, it is
bound to have a fracture with propagation trend whose long axis shows an angle of $\beta$ with the maximum principal stress and suffers tensile fracturing at the ends of the fracture with propagation trend. As shown in Equation (8), $\beta$ in the direction along which fractures are likely to extend is determined by $\sigma_1$ and $\sigma_3$, and there are different $\beta$ values under different combinations of $\sigma_1$ and $\sigma_3$, as shown in Figure 6.

According to the analysis in the last section, stresses $\sigma_1$ and $\sigma_3$ in the coal and rock in the floor obviously change under the influence of mining No. 2 coal seam in the upper part. Such changes further transfer and affect the mechanical behaviors of cracks in floor strata.

When $\sigma_1 > 0$ and $\sigma_3 > 0$, the stress relationship meets Equation (6) and the angle of the fracture with the propagation trend satisfies Equations (7) and (8). Based on Equation (7), $\frac{1}{2} > \cos 2\beta > 0$, that is, $45^\circ > |\beta| > 30^\circ$ and the angle between the long axis of the fracture and the maximum principal stress $\sigma_1$ is in the range of $[30^\circ, 45^\circ]$ or $[-45^\circ, -30^\circ]$. Tensile failure is likely to occur in the local areas after fracturing, expansion and deformation of the coal and rock mass in the floor and mining-induced secondary horizontal tensile stress $\sigma_3 < 0$ appears. When $-8R_1 > \sigma_3 > 0$ and $0 > \sigma_3 > R_1$, according to Equation (7), $0 > \cos 2\beta > \frac{1}{2}$, that is, $|\beta| < 30^\circ$ and the angle between the long axis of the fracture and vertical stress is in the range of $[-30^\circ, 30^\circ]$.

Based on the above, when $\sigma_1 > 0$ and $\sigma_3 > R_1$, $|\beta| < 45^\circ$, that is, the angle $\beta$ between the long axis of the fracture with the propagation trend and the maximum principal stress is any value in the range $[0^\circ, 45^\circ]$.

According to the above analysis, when mining-induced secondary tensile stress is not considered, that is, $\sigma_3 > 0$, the vertical stress is larger than the horizontal stress when the coal and rock mass in the floor is in the compression zone. In this zone, $\sigma_1 = \sigma_2, \sigma_3 = \sigma_2$ and $\sigma_1 > \sigma_2 > 0$. Moreover, $45^\circ > |\beta| > 30^\circ$ and the angle between the long axis of the fracture and vertical stress is in the range of $[30^\circ, 45^\circ]$ or $[-45^\circ, -30^\circ]$. Therefore, the fracture with propagation trend tends to develop in the vertical direction. When the coal and rock mass in the floor is in the expansion zone, the horizontal stress is larger than the vertical stress. Therefore, $\sigma_1 = \sigma_2, \sigma_3 = \sigma_2$ and $\sigma_1 > \sigma_3 > 0$. At this time, $45^\circ > |\beta| > 30^\circ$, and similarly, the angle of the long axis of the fracture with the horizontal stress will be in the range $[30^\circ, 45^\circ]$ or $[-45^\circ, -30^\circ]$. Hence, the fracture with the propagation trend is inclined to develop in the horizontal direction. Similarly, when the coal and rock mass in the floor exist in the transition zone, the maximum principal stress is changed from vertical stress to horizontal stress, and the direction of the fracture with the propagation trend varies from the vertical direction to the horizontal direction with the maximum principal stress. In addition, as the coal and rock mass in the floor is in the recompaction zone, the vertical stress grows again and the angle of the fracture with the propagation trend in the surrounding rock is approximately vertical.

In conclusion, during mining, the coal and rock strata in the floor are subjected to continuous and periodic failure during advancement of the upper working face. The angle of the fractures with the propagation trend extending in different zones of the floor changes periodically, and the fractures are crossed and overlapped, thus forming a mining-induced fracture network, as shown in Figure 6.

3.2 | Accurate characterization of the fracture field in the floor and the verification test

The aim of this section is to improve the reliability of the simulation results and reasonably reduce the computational time required for simulation. For this purpose, in view of the large-scale excavation during underground coal mining, this study adopted the discrete element simulation software 3DEC and bonded block model (BBM) to simulate the distribution and evolution of mining-induced fracture field during excavation of short-distance coal seams. Moreover, the feasibility of practically applying this method coal mining is also discussed. The research results can deepen the understanding on the stress field and fracture field produced by coal seam mining and can provide certain references for the mining practice in coal mine, such as the estimation of failure depth in the roof and floor and the arrangement of boreholes for gas drainage in coal seam groups.

3.2.1 | Overview of working face 22201 in Shaqu coal mine

Working face 22201 is located in the coal seam 2# in the Shaqu coal mine. The coal is extracted by totally mechanized
coal mining. It is 150 m wide and 1516 m long in its advance direction. The surface elevation ranges from +822 m to +1007 m, and the elevation of the 2# coal seam is between +396 m and +486 m. This coal seam has relatively uniform properties and distributes across the coal mine. Its average dip angle is about 4°, and average thickness is 1.1 m. The geologic histogram is shown in Figure 7.

3.2.2 Establishment of BBM-DEM numerical model

By utilizing the bonded block model-distinct element modeling (BBM-DEM) simulation method, numerical analysis was performed on the mining-induced fracture field on the 22201 working face in No. 2 coal seam in Shaqu coal mine. This accurately revealed the dynamic evolution laws of mining-induced fracture field during mining of the protective seams, verifying that the method is feasible.

Based on the geological conditions of the second mining area in the north of Shaqu coal mine, the BBM-DEM calculation model was established after reasonably simplifying the model. Figure 8 shows the establishment, boundary conditions, and strata of the numerical simulation model as well as partially enlarged details corresponding to a tetrahedron block. It should be noted to notice that in order to improve the calculation efficiency, the speeds of all nodes in the model with dimension of a 220 × 1 × 200 m (Figure 8A) are fixed along the Y direction, thus simplifying the three-dimension (3D) problem into a problem of two-dimension plane strain in the calculation. During the modeling process, tetrahedron blocks corresponding to medium sandstone on the top and bottom of the model have a side length of 4 m, and the coal seam and adjacent rock strata of interest correspond to tetrahedron blocks with a side length of 1 m. The model takes 18 layers of coal and rock mass into account and there are 81 052 tetrahedron blocks in total. If the model is built into a 3D model (220 m along the Y direction), there will be about 18 000 000 tetrahedron blocks. At present, it is impossible to perform such a large amount of computation on ordinary workstations or personal computers. As shown in Figure 8A, the left and right sides of the model are the displacement boundary conditions, which limit the movement of each block in the horizontal direction, while the fixed boundary condition is applied to the bottom of the model. The stress boundary condition is applied to the top of the model where the load is the self-weight of the overlying strata. Since the burial depths of No. 2 coal seam and the top of the model are about 500 m and 450 m, respectively, the in situ rock stresses applied on the top of the model are $\sigma_v = 10.3$ MPa, $\sigma_H = 7.73$ MPa and $\sigma_h = 3.59$ MPa based on the research of Kang et al\textsuperscript{18} on the in situ stress field in Shanxi coal mines. The flowchart of the numerical analysis is as follows: establishing the BBM-DEM model, applying reasonable boundary conditions, selecting the deformation and strength parameters of blocks and contact surface, applying the in situ stress field, initially balancing the stress field, excavating No. 2 protective coal seam (a calculation cycle involves excavation of 10 m and 50 m separately in the left and right sides), finishing simulation, and analyzing simulation and calculation results.

3.2.3 Evolution characteristics of mining-induced fracture field

The aim of this section is to explore the evolution characteristics of fractures in the floor strata in the advance process of the upper coal seam under the condition of a coal seam group. For this purpose, this study calculated and analyzed mining-induced floor fractures at different advance distances of the 22201 working face in Shaqu coal mine by using the BBM-DEM detailed simulation method based on the same geological conditions. The results are shown in Figure 9.

Figure 9A shows the movement laws of the overlying strata and the distribution of fractures when the working face is advanced by 40 m. It can be seen from the simulation that the bedrock does not fracture and sink at this time, while the immediate roof is caved in a large range. Meanwhile, there is certain space between the caved rock blocks and bedrock. Floor fractures are developed in the lower part of the goaf and a certain range on both sides of the goaf, but they do not extend to the lower coal seams. As the working face is advanced to 70 m, as shown Figure 9B, the bending moment increases and exceeds the strength limit of the rock strata with the increase in hanging area of the main roof, therefore, the first buckling failure occurs on the main roof, showing the first weighting of the working face. Floor fractures are still distributed in the entire lower part of the goaf and a certain range on both sides of the goaf, but they do not extend to the lower coal seams. As the working face is advanced to 100 m, as shown in Figure 9C, buckling failure happens on the main roof again. With constant caving and backfilling of the overlying strata in the goaf, it can be seen that the number and development degree of floor fractures at about 40 m in the rear of the working face begin to reduce. This indicates that rocks caved in this place are gradually compacted again and the stress starts to recover. With advancement of the working face to 120 m, as shown in Figure 9D, buckling failure takes place again on the main roof and the floor fracture group moves forward with the advancement of the working face. In addition, the distribution law of floor fractures is approximately the same as that when the working face is advanced to 100 m. This demonstrates that the floor fractures have propagated to the largest range.

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3.2.4 Characteristics of dip angles of floor fractures at different advance distances

A statistical analysis of the distribution (acute angle with a horizontal line) of fracture angles, with respect to different advance distances, in the coal and rock in the floor of the working face being mined in the upper No. 2 coal seam was conducted. The analysis results are summarized in Table 1 and Figure 10. This analysis was based on the results of the BBM-DEM detailed simulation.

We can conclude from the aforementioned results that the combination of fractures with large and small angles in the coal and rock in the floor being mined constantly changes with the increase of the advance distance of the working face and pressure relief range in the floor. From the advancement at the open-off cut of the working face, the number and proportion of fractures with a small angle (≤30°) in the floor being mined gradually increase and, respectively, reach 81% and 55.1% in advanced 100 m working face. This is mainly due to the pressure relief of the floor being mined, great
3.2.5 | Characteristics of dip angles of floor fractures in different zones

To further explore the distribution characteristics of fractures in coal and rock strata in the floor of the coal seam after complete mining, this study analyzed the distribution characteristics of dip angles of fractures in different zones of the floor at an advance distance of \( L = 100 \) m of the working face, as shown in Table 2.

In the coal and rock strata in the compression zone of the floor, the weight of overlying strata is transferred and concentrated due to the mining of coal seams in the section that is 8-40 m in front of the working face. Therefore, in this zone, all mining-induced fractures in the coal and rock of the floor under the effects of higher vertical stresses are compression-shear fractures with a large angle (≥60°).

In floor strata, in the transition zone ranging from 8 m in front to 2 m in rear of the working face, horizontal stress changes slightly, while vertical stress sharply decreases. In the zone, fractures with medium and small angles (<60°) develop, accounting for 59.4%.

In the expansion zone ranging from 2-40 m behind the working face in the floor strata, the vertical stress is sufficiently released due to mining. Under the dominant effects of the horizontal stress, coal and rock strata in the floor in this zone mainly show fractures with medium and small angles approaching horizontal beddings, in which proportion of fractures with a small angle (≤30°) increases to 41.5%.

In the recompression zone at the rear of the expansion zone, because of recovery and compaction of the vertical stress, fracture closure reduces and the total number of fractures decreases to 47. In comparison with the expansion zone, fractures with a small angle (≤30°) reduce by 30, which accounts for 71.4% of the total reduction in fractures.

Based on the aforementioned analysis, it can be concluded that the key factor influencing changes in angle and number of fractures in the floor of the working face being mined is the change in vertical stress. In the zone with high degree of pressure relief, fractures with a small angle are developed; otherwise, fractures with a large angle are developed.

3.2.6 | Verification test

Gas contents of the No. 2, No. 3 + 4, and No. 5 coal seams in Shaqu coal mine are 4.50-10.12, 5.49-12.46, and 5.00-12.84 m³/t, respectively. During the stoppage of the 22201 working face, in order to prevent the gas from exceeding the limit in the working face due to gas overflow from adjacent strata, grid-based cross-measure boreholes for gas drainage were drilled upward, with 10 × 10 m spacing in the upper coal seam group from the floor roadway. The purpose was to intercept the overflow of gas in the No. 3 + 4 and No. 5 coal seams, as shown in Figure 11. To study the influence of stress and fracturing characteristics of coal and rock in different zones of the floor on gas drainage, this study observed the gas flow, the concentration, and the pure quantity of gas drained from drainage boreholes in the compression and transition zone, the expansion zone, and the recompression zone.
(as the transition zone is narrow and stresses in the compression zone and transition zone are larger than the original state, for the convenience of practical operation, the two zones are merged for observation). The parameters of average drainage results in a single borehole are presented in Table 3.

As demonstrated in Table 3, the flow, the concentration, and the pure quantity of gas drained from drainage boreholes in the expansion zone of the floor being mined are much higher than those in other zones. By combining with the existing analysis and conclusions, it is considered that reduction of stress unloading in the expansion zone and full development of fractures are favorable for improving permeability of coal seams and desorbing absorbed gas. In the meanwhile, the fracture angle in the expansion zone of the floor is mainly dominated by bedding fractures with a small angle, which is beneficial for gas in coal seams to flow and concentrate to drainage boreholes. On the basis of the aforementioned factors, better effects of gas drainage are obtained in this

### Table 1
Statistical analysis of distribution of fracture angles in coal and rock strata in the floor under different advance distances of the working face

| Dip angle of fracture | Location | 40 m (Caving of immediate roof) | 70 m (First weighting) | 100 m (Second weighting) | 120 m (Third weighting) |
|-----------------------|----------|---------------------------------|------------------------|--------------------------|-------------------------|
|                       | Number   | Proportion (%)                  | Number                 | Proportion (%)            | Number                  | Proportion (%)            |
| ≤30                   | 51       | 41.6                            | 63                     | 50.4                     | 81                      | 55.1                     | 72                      | 39.5                   |
| 30–45                 | 9        | 9.2                             | 14                     | 11.2                     | 17                      | 11.5                     | 28                      | 15.5                   |
| 45–60                 | 19       | 17.6                            | 15                     | 12                       | 8                       | 5.4                      | 19                      | 10.3                   |
| ≥60                   | 29       | 31.6                            | 33                     | 26.4                     | 41                      | 27.9                     | 65                      | 35.7                   |
| Total                 | 108      | 100                             | 125                    | 100                      | 147                     | 100                      | 184                     | 100                    |

Note: In the model, it is assumed that the open-off cut of the working face only locally affects the local trend of the floor and the number of fractures in coal and rock strata in the floor can be neglected as zero.

### Figure 10
Distribution and evolution of angles of mining-induced fractures in the floor of the coal seam at different advance distances: (A) 40 m, (B) 70 m, (C) 100 m, and (D) 120 m
zone. The parameters of drainage results of each borehole in the compression and transition zone are lower than those in other zones because although there are fractures in surrounding rocks, due to high stress in the compression zone, gas is difficult to desorb and flow under high confining pressure. Drainage flow of boreholes in the recompaction zone largely decreases compared with the expansion zone but still higher than that in the original zone. This indicates that stress in the floor is incompletely recovered despite collapse and compaction of the overlying rock, that is, after mining the upper coal seams, stress of coal and rock in the large recompaction zone of the floor in the rear of goaf maintains at a relative relief state for a long term.

4 | CONCLUSIONS

In summary, based on the distribution laws of mining-induced stress in the floor, this study obtained characteristics of stress zones in the floor of the coal seam while mining the 22201 working face in Shaqu coal mine. The propagation laws of fractures in different stress zones in floor strata of the coal seam were theoretically analyzed using the Griffith criterion, and the distribution laws of fracture angles in floor strata under different mining-induced stress states were obtained. The following main conclusions can be made from this study:

1. During multi-seam mining, the floor stress in front and rear of the working face changes in the form of a continuous parabola. Fluctuation in vertical stress is more sensitive than horizontal stress. In addition, the change in amplitude and gradient are larger in case of vertical stress than those of horizontal stress in the same zone. The stress of the coal and rock in the floor in front and rear of the working face is divided into four zones, that is, the compression zone, the transition zone, the expansion zone, and the recompaction zone.

2. The increase of concentration degree, unloading-induced reduction, and recovery of vertical stress of the floor can directly affect the distribution characteristics of combinations of fractures with high and low angles in coal and rock in the floor. In the compression zone, due to increase of the concentration degree of vertical stress, mining-induced fractures with a larger angle (>60°) mainly appear. In the transition zone and the expansion zone, with unloading-induced reduction of vertical stress, fractures with a small angle grow, develop, and reach the highest proportion in the expansion zone. In the recompaction zone, the proportion of fractures with a large angle (>60°) increases to 44.7%.

3. While advancing working face in the overlying coal seams in a coal seam group, the flow of gas to boreholes is
facilitated by the complete stress unloading and development of mining-induced fractures, which are dominated by fractures with a small angle in bedding direction. Therefore, the concentration and pure quantity of gas in cross-measure boreholes in the expansion zone are high. Thus, this region is the ideal zone for gas drainage in the mining of the upper protected seam.

ACKNOWLEDGMENTS
The authors acknowledge financial support provided by State Key Research Development Program of China (2017YFC0804206), National Natural Science Foundation (51604154 and 51704046), National Science and Technology Major Project of China (2016ZX05067-005), and the Fundamental Research Funds for the Central Universities (3142019005).

TABLE 3  Statistics of average gas drainage results in a single borehole in different zones of the floor

| Category                      | Original zone (<−40 m) | Compression and transition zone (−40 to 2 m) | Expansion zone (2−40 m) | Recompaction zone (>40 m) |
|-------------------------------|-------------------------|---------------------------------------------|--------------------------|---------------------------|
| Flow (×10^{-3} m^3 min^{-1}) | 13.5                    | 8.5                                         | 22.4                     | 16.8                      |
| Concentration (%)             | 33.4                    | 30.2                                        | 51.6                     | 29.5                      |
| Pure quantity \((×10^{-3} m^3 min^{-1})\) | 4.5                     | 3.4                                         | 11.6                     | 4.9                       |

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How to cite this article: Cheng Z, Ouyang Z, Zou Q, Lu Y, Zhao X, Li M. 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;8:1620–1633. [https://doi.org/10.1002/ese3.620](https://doi.org/10.1002/ese3.620)